JOURNAL
OF
GEOMAGNETISM
AND
GEOELECTRICITY

VOL. VI NO. 4

Special Number for the Proceedings of the Palaeomagnetism Session, International Association of Terrestrial Magnetism and Electricity, Rome 1954

SOCIETY
OF
TERRESTRIAL MAGNETISM AND ELECTRICITY
OF
JAPAN

DECEMBER 1954

KYOTO

JOURNAL OF GEOMAGNETISM AND GEOELECTRICITY

The fields of interest of this quarterly Journal are as follows:

Terrestrial Magnetism	Aurora and Night Airglow
Atmospheric Electricity	The Ozone Layer
The Ionosphere	Physical States of the Upper Atmosphere
Radio Wave Propagation	Solar Phenomena relating to the above Subjects
Cosmic Rays	Electricity within the Earth

The text should be written in English, German or French. The price is set as 1 dollar per number. We hope to exchange this Journal with periodical publications of any kind in the field of natural science.

The Editors

Preface

All articles on palaeomagnetism compiled in this special number of Journal of Geomagnetism and Geoelectricity are those which were presented to the 10th General Assembly of the International Association of Terrestrial Magnetism and Electricity held at Rome in September, 1954. In the session on palaeomagnetism of the Rome Meeting of I.A.T.M.E., reliability of rocks' magnetism as an indicator of the geomagnetic field in remote epochs and the results of palaeomagnetic studies with the aid of the rocks' magnetism were chiefly discussed by many attendants of various nationalities. One of the main topics was interpretation of reverse magnetisation of rocks, especially in connection with the secular variation of the direction of the earth's dipole field in geologic times.

Since such a problem deals with a global phenomenon, its studies must be carried out by refering to a large number of rock-samples collected from various localities over the earth. The session on palaeomagnetism of the Rome Meeting was the first international conference formally organized for this special subject, and remanent magnetisation of igneous, sedimentary and metamorphosed rocks in England, France, Iceland, Japan and the United States was discussed from the view point of palaeomagnetism. Under the circumstance, it will be convenient for those who are interested in this subject to publish the main articles read before the Rome Meeting in a special number of a scientific publication. Fortunately, the Society of Terrestrial Magnetism and Electricity of Japan had agreed to publish those articles in a volume of the Journal of Geomagnetism and Geoelectricity. I would like to express my sincere thanks to Professor M. Hasegawa, President of the Society, and the other members of the editorial board of the Journal for their courtesy of willing acception of our request.

Among thirteen full papers presented to the Meeting, twelve papers are printed in this volume after the authors' revision of the original manuscripts, while unfortunately Prof. E. Thellier does not wish to publish his article in this synthetic report. For the sake of the readers' convenience, however, an abstract of Prof. Thellier's article is printed here together with that of Dr. J. W. Graham's article which was expected to be presented to the Meeting.

Although, as mentioned above, this publication is not perfect as the proceeding of the session on palaeomagnetism of the I.A.T.M.E. Assembly, I trust that it covers almost all the main topics discussed there. I hope therefore that this publication is valuable for the purpose of further development of palaeomagnetism. At this opportunity, I would like to express my gratitude to the authors of the

individual articles contained in this volume for their continuous cooperation for the organization of the session on palaeomagnetism and the compilation of this volume.

March 1, 1955

Takesi NAGATA

Chairman, Special Committee of Secular Variation
and Palaeomagnetism, I.A.G.A.

The Direction of the Geomagnetic Field in Remote Epochs in Great Britain

By K.M. CREER, E. IRVING and S.K. RUNCORN
Department of Geodesy and Geophysics, University of Cambridge

Abstract

The remanent magnetizations of samples of sediments and lavas from Great Britain, representative of widely different geological epochs, have been studied. Evidence for the stability of these magnetizations from times soon after the formation of the rocks has been found. These results seem most easily interpreted in terms of a dipole field, the polarity of which frequently reverses. In Pre-Tertiary times the axis of this dipole field diverges considerably from the present geographical axis and this is tentatively interpreted as a slow change in the axis of rotation of the earth with respect to its surface.

In 1950 an investigation into the direction and the physical properties of magnetisation of rocks was started at the Dept. of Geodesy and Geophysics. At first igneous rocks were studied but the construction of a sensitive astatic magnetometer enabled a systematic study of the magnetization of sediments to be begun in 1951.

Measurements have now been made on sediments from all geological periods right back to the late Pre-Cambrian. The stability of magnetisation has been studied and the results given here are restricted to those rocks whose stability can be proved with a reasonable degree of certainty by either field or laboratory tests.

It has been necessary to invoke three hypotheses in order to interpret the results satisfactorily.

(1) That averaged over several thousands of years, the geomagnetic field at the earth's surface is a geocentric dipole with its axis along the axis of rotation.

(2) That the geomagnetic field, at certain times in the remote past, has reversed in polarity.

(3) That polar wandering has occurred i.e. the earth has toppled over gradually through geological time with respect to its axis of rotation.

1. Directions of Magnetisation and Polar Wandering

Detailed work has been done by E. Irving on the Torridonian Sandstones of N.W. Scotland. These are of late Pre-Cambrian age. Sixty-three localities representative of a 9,000 ft. thick succession have been sampled. The localities can be grouped into sixteen zones with alternating opposed magnetisations, the

thicknesses of these zones varying from 100 ft. to 2,000 ft. The mean directions of magnetisation are strongly oblique to that which would be produced by the present geomagnetic field. The directions are summarised below:

Table 1

Sign of dipole field	Declination (averaged values)	Inclination (averaged values)	No. of Localities
−	N 65° W	−34°	16
+	S 53° E	+52°	37

In addition ten localities have been found with directions of magnetisation significantly different from these prevalent directions. It is however worthy of note that these localities are sandwiched between oppositely magnetized zones and the directions are thought to be those of the transitional geomagnetic fields during the period (probably relatively short) when reversals are actually occurring.

K.M. Creer has investigated the major directions of magnetisation of sediments varying in age from Pre-Cambrian to Triassic.

The Wentnor Series of the Pre-Cambrian of the Longmynd in Shropshire is very similar lithologically to the Torridonian Sandstones and many geologists have vaguely suggested that they are not very different in age. The tectonic structure here is complicated but when corrections have been made for the tilt of the beds (almost vertical) the directions of magnetisation are similar to those found in the Torridonian sandstones. It has not been possible to group the localities from which samples have been collected into zones of opposed magnetisation but examples of both magnetisations have been found.

The Caerfai Series (Early Cambrian) has been sampled at St. David's in Pembrokeshire. A 1,000 ft. coastal exposure exhibits southward polarisation only. No Ordovician Sediments yet sampled have been found suitable but samples from the Ludlow Series (late Silurian) in Pembrokeshire exhibit southward polarisation.

A more comprehensive study has been made of the Old Red Sandstone (Devonian) rocks of the Anglo-Welsh cuvette. Thirty localities have been sampled from Pembroke in the West to Gloucester in the East and from Bristol in the South to Ludlow in the North. Of these only two localities show normal polarisation and both these occur in the Downtonian. The whole of the Dittonian and Upper Old Red Sandstone exhibits southward polarisation exclusively.

Five traps of the Exeter Volcanic series (Permian) all show reversed polarisation, the axis of magnetisation being close to that given by the Old Red Sandstone sediments. Provisional directions from the Permian Lavas of the Midland Valley of Scotland, investigated by P.M. Du Bois of this department, are substantially the same.

Samples taken from a 110 ft. cliff of Keuper Marl at Sidmouth in Devon are only partially stable but there is strong evidence of magnetisation along a N.E.–S.W. axis with small angles of dip. The upper part of the cliff is magnetised N. E. but

the lower part is magnetised S.W. The thickness in which a reversal occurs is

Fig. 1

Table 2

Geological Period	Averaged Directions	Sign of Field	Position of Geographical Poles
Pre-Cambrian[1] (Longmyndian)	N56°W−38° S69°E+19°	− +	N. Pole—Middle of Pacific 130°W 0° S. Pole—Near Ethiopia 50°E 0°
Cambrian	S 7°W+39°	+	N. Pole—Marshall Is. in Pacific 173°E 15°N S. Pole—St. Helena, of S. Atlantic 7°W 15°S
Silurian	S25°W−16°	+	N. Pole—140°E 40°N Japan. N. Honshu S. Pole—40°W 40°S in S. Atlantic
Devonian	N34°E+2° S19°W−2°	− +	N. Pole—In Pacific east of Tokyo 156°E 34°N S. Pole—S. Atlantic about 3,000 miles S.E. of Buenos Aires 24°W 34°S
Permian	S 9°W−9°	+	N. Pole—In Pacific Nr. Kamchatka S. Pole—3,000 miles N.E. of Buenos Aires
Triassic	N26°E+26° S°34W−26°	− +	N. Pole—In Pacific Nr. Kamchatka 133°E 47°N S. Pole—In S. Atlantic 47°W 47°S
Eocene[2]	S14°W−60°	+	N. Pole—In Arctic Laptev Sea 118°E 75°N S. Pole—62°W 75°S in Weddell Sea Antarctica

1. Compare with Table 1
2. J. Hospers and H.A.K. Charlesworth, Geophys. Suppl., M.N.R.A.S., 7, 32–43, (1954)

certainly less than 3 ft.

The post-Triassic rocks of the Mesozoic and the Tertiary sediments sampled to date have been found to be unstable in the earth's field.

These palaeomagnetic directions are summarised in tables 1 and 2. It is convenient to express them in terms of a former position of the magnetic poles, assuming no continental drift. The coincidence of the axis of rotation with the magnetic axis is assumed and the north geographical poles for each epoch are taken to be those which lead to a smooth variation of the axis through geological time. A sign of the field can therefore be assigned, positive when the dipole is parallel to the angular velocity vector and negative when antiparallel. Thus the present field is negative. The data are tabulated in table 2 and illustrated in Fig. 1 by the heavy line.

2. Stability and Origin of the Natural Remanent Magnetisation.

(a) *Field Tests.*

(i) Conglomerate pebbles.

The present directions of magnetisation of Torridonian fine sandstone and siltstone pebbles in conglomerates of New Red Sandstone age are completely random. This suggests that the original magnetisation has remained stable for a few hundred million years.

(ii) Folds.

Samples taken from anticlinal and synclinal folds show similar directions of magnetisation with respect to the bedding planes to those obtained for flat lying beds of similar age. The following structures have been investigated:

Torridonian beds folded during the Caledonian orogeny.

Longmyndian beds folded during the Caledonian orogeny.
(synclinal overfold with nearly vertical limbs, a few miles apart.)

Old Red Sandstone beds folded during the Hercynian Orogeny.
(anticlinal structure at Freshwater East, Pembrokeshire, limbs vertical, "half wave-length" 1 mile).

There is evidence that the Old Red Sandstone beds in Pembrokeshire received a thermo-remanent magnetisation of about a quarter the intensity of the natural remanent magnetisation after folding and during burial at depth in a reversed field having a small inclination to the horizontal. Laboratory tests show that a temperature of 100°C to 200°C would be sufficient to do this.

(iii) Slumped Beds.

The directions of magnetisation of both small and large scale slumped beds of Torridonian Siltstone have been studied. In the former the directions are practically random, as though the magnetisation took place at deposition and the directions were disturbed by the slumping. Specimens from the large scale slumps, however, are uniformly magnetised in the same direction as adjacent flat lying beds. This implies that the beds were remagnetised after slumping had occurred.

(iv) Dispersion and Grain Size.

It has been found, particularly in the Torridonian, and in some cases in the Old Red Sandstone, that siltstone and fine-grained sandstones exhibit a much smaller dispersion of magnetisation directions within a given rock sample than do coarser grained sandstones. This is consistent with a depositional magnetisation but not necessarily with a chemical or thermo-remanent magnetisation.

(b) *Laboratory Tests.*

The sediments sampled are conveniently divided into three groups:

1. Those which are completely stable in the earth's field.
2. Those which are partially stable in the earth's field.
3. Those which are completely unstable in the earth's field.

It seems that there are two components of magnetisation present in most of the rocks investigated, a "hard" component (due probably to black detrital grains of haematite) and a "soft" component (due in many cases to a red haematite cement, the small particles of which have small relaxation times because of the demagnetising effect of thermal fluctuations). (See Natural Magnetisation of Igneous and Sedimentary Rocks—Nature, 173, 1114–1122 (1954). The relative intensity of these two components decides into which of the above groups a given rock falls.

All the rocks from which the data contained in the "polar wandering" table have been compiled fall into the first group. No significant change in polarisation has occurred in these rocks when left in the earth's field for a year.

The Keuper Marls at Sidmouth fall into the second group. These rocks contain about the same amount of red haematite cement as the stable rocks, but the total intensity is lower. Magnetic separation yields about one tenth of the amount of black detrital haematite as the "stable" rocks of group 1. When specimens are left in the laboratory for a few weeks the directions of magnetisation rotate by amounts up to about 30° to 40°, the change being towards the direction of the earth's field. The rate of rotation decreases with time and the direction of magnetisation does not change much after a few months. The specimens never become magnetised completely in the direction of the applied field.

Keuper Marls from Beachley, the intensity of magnetisation of which is considerably less than those from Sidmouth are completely unstable in the earth's field. On being left in the laboratory for weeks specimens were found to have become remagnetized almost completely in the direction of the earth's field.

3. **Ferromagnetic Mineral Identification.**

All the Torridonian, Longmyndian, Old and New Red Sandstone rocks sampled have been passed through a magnetic separator. The black detrital mineral so obtained has been subjected to X-ray and magnetic analysis.

In all cases, whether the rock sample shows normal or reversed polarisation, the mineral has been identified as haematite, αFe_2O_3. It has not been possible to find any difference at all between extracts from normal and reversely polarised samples. The mineral possesses a saturation magnetisation of about 0.4 e.m.u./gm. It has a Curie point of about 680°C. The back field (H_b) required to destroy its

saturation magnetisation is 1600 oersteds. Samples of this mineral have been studied under the ore microscope by R. Phillips of the University of Durham. He finds that many of the grains, identified by X-ray analysis as haematite are in fact intergrowths of haematite and leucoxene exhibiting a triangular texture indicating a cubic host. Some of these grains contain what appear to be magnetite remnants in amounts too small to be detected by X-ray powder photographs.

The back field (H_b) required to destroy the maximum magnetisation of the whole rock varies from 2,000 oersteds to 10,000 oersted. Often it has been found impossible to saturate these rocks in a field of 12,000 oersteds. Mlle. Roquet found that a field of 30,000 oersteds was necessary to saturate finely divided αFe_2O_3 and the large values of H_b for the whole rock is attributed to the presence of the red cement.

4. **Conclusions.**

Reversals of polarisation seem not to be confined to Tertiary strata or to igneous rocks. The coincidence of the magnetic and rotational axes in Tertiary time covering many reversals is explained by the dominance of the Coriolis force on motions within the earth's core [1] and is thus likely to have been true in other eras.

The oblique mean axes of magnetisation found in Pre-Tertiary times are therefore simply explained by the polar wandering hypothesis. Since the rocks have been collected from Britain only, it is impossible yet to exclude continental drift as the cause of the change in the various ancient pole positions. When measurements have been made on rocks from several continents it should be possible to test whether or not polar wandering is a sufficient explanation. Figure 1 shows the position of the poles inferred from geological evidence by Köppen, Wegener and others. It will be seen that this motion of the pole is more rapid than that inferred from rock magnetism, although it is in the same general region of the world.

Reference

[1] S.K. Runcorn, Trans. Amer. Geophys. Un. 35, 49-63, (1954).

Exposé Sommaire des Etudes Relatives à l'Aimantation de Matériaux Volcaniques

Par A. ROCHE
Institut et Observatoire de Physique du Globe du Puy de Dôme,
Université de Clermont

Résumé

L'auteur rappelle très brièvement les résultats qu'il a obtenus au cours de recherches effectuées de 1947 à 1953 sur les roches volcaniques d'Auvergne et du Velay.

Les inversions d'aimantation constatées paraissent caractériser tous les matériaux volcaniques de certains âges quelle que soit leur nature pétrographique.

Ces observations semblent favorables à l'hypothèse d'inversions réelles du champ magnétique terrestre qui se seraient répétées plusieurs fois durant L'Ere Tertiaire.

Les roches étudiées jusqu'à présent appartiennent toutes au Massif Central de la France (Auvergne et Velay). L'époque de leur mise en place varie depuis le Tertiaire moyen (Stampien) jusqu'au Quaternaire récent. Elles appartiennent à des types pétrographiques variés (trachytes, andésites, téphrites, basaltes). Des specimens d'argiles ou de marnes pris au voisinage de masses volcaniques ont été aussi étudiés.

Les principaux résultats obtenus sont les suivants:

1/ A l'exception d'anomalies très localisées, une même unité volcanique: coulée, dyke ou neck, est caractérisée par une direction et un sens d'aimantation qui lui sont propres.

2/ Les directions d'aimantation observées s'écartent relativement peu de la direction actuelle du champ magnétique terrestre au lieu considéré.

3/ Le sens d'aimantation est soit le sens du champ terrestre actuel, soit le sens inverse.

4/ Les roches du Quaternaire récent ont un sens d'aimantation en accord avec celui du champ terrestre actuel (sens normal).

5/ Les roches plus anciennes ont une aimantation, soit de sens normal, soit de sens inverse.

6/ Le groupement des aimantations normales et inverses parait se faire en fonction de l'âge des roches étudiées.

J'ai observé des aimantations de sens inverse pour les périodes suivantes:

Pléistocène ancien et Pliocène récent (Villafranchien). Limite du Pliocène

inférieur et du Miocène supérieur (Astien-Pontien), Oligocène (Stampien supérieur-Aquitanien).

7/ Les argiles et marnes récoltées au voisinage immédiat de roches volcaniques à aimantation inversée ont toujours présenté aussi une aimantation inversée bien que leurs constituants minéralogiques soient d'origine indépendante.

Interprétation des faits observés :

2 hypothèses sont en présence :

l'une attribuant les inversions d'aimantation à des inversions réelles du champ magnétique terrestre, l'autre attribuant les inversions au jeu de mécanismes internes à la roche, le champ magnétique terrestre ayant gardé un sens constant. La valabilité de cette 2^e^ hypothèse a été confirmée à la suite des études théoriques de L. Néel et des résultats expérimentaux obtenus par T. Nagata. Les nombreux travaux de laboratoire effectués (J. Graham, J. Hospers, T. Nagata, J. Roquet, E. Thellier ect) ont montré des aspects nouveaux et intéressants de la question, mais n'ont pas apporté d'argument décisif en faveur de l'une ou de l'autre hypothèse. On peut retenir comme arguments favorables à l'hypothèse de changements de sens effectifs du champ magnétique terrestre le fait que les aimantations se groupent selon l'âge des roches et le fait que les argiles et marnes récoltées au voisinage de roches volcaniques présentent le même sens d'aimantation qu'elles.

Suggestions proposées pour les recherches ultérieures sur le terrain.

1/ Récolter chaque fois que cela est possible des roches sédimentaires au voisinage immédiat de coulées ou de dykes et vérifier le sens de leur aimantation comparativement à celui des roches volcaniques.

2/ S'attacher à récolter des échantillons volcaniques bien datés. Les méthodes radioactives donnent une précision relative faible pour le tertiaire récent et le quaternaire. On pourrait utiliser la méthode stratigraphique en examinant de préférence des coulées encadrées par des couches sédimentaires fossilifères.

Les intervalles de temps pendant lesquels les aimantations paraissent garder un sens constant sont brefs par rapport aux durées des périodes géologiques et l'on ne peut guère espérer établir une corrélation chronologique entre les résultats obtenus en différentes régions du globe pour des roches assez anciennes.

Par contre il serait intéressant de préciser la date de la mise en place des roches à aimantation inversée du Pléistocène ancien et du Villafranchien. Si l'on parvenait à établir pour cette période des dates limites entre lesquelles toutes les roches observables présentent l'aimantation inversée et à l'extérieur desquelles elles présentent l'aimantation normale, on aurait là un argument très fort en faveur de changements de sens réels du champ terrestre et un espoir de rattacher ces changements à un caractère astronomique ou géologique de l'histoire du globe.

Fig. 1 Diagramme de la fréquence des unités volcaniques en fonction de la direction de leur aimantation thermorémanente.

Summary of Studies on Rock Magnetism

By J. HOSPERS
N.V. De Bataafsche Petroleum Maatschappÿ-Royal Dutch/Shell Group;
formerly at the Department of Geodesy and Geophysics,
University of Cambridge

Abstract

A series of abstracts is given of papers recently published by the author. The main conclusions reached are that the earth's magnetization has suffered repeated reversals, and that rock magnetism can be used for geological correlation and for studies of continental drift and polar wandering.

At the request of Professor T. Nagata, Special Reporter on palaeomagnetism of the "Association de Magnétisme et Electricité Terrestres" for the Rome Assembly, September 1954, the present author has prepared the following summary of his work on rock magnetism.

In 1950 work was started on Icelandic lava flows and sediments, ranging in age from Miocene to the present day, that is, from about 20 millions years ago to the years 1947-48, when the latest eruption of Mt. Hekla took place. The first few results were published in a short note [1], the complete results were embodied in the author's thesis [2], which was summarized in a later series of papers [3].

The following conclusions have been reached:

a. The normal natural permanent magnetization of the lava flows in Iceland originated when they cooled down for the first time after their formation. This magnetization was acquired in the direction of the local geomagnetic field at that time. This magnetization (thermo-remanent magnetization) has been stable in direction over periods of millions of years and therefore may be assumed to have been stable since it originated. The intensity of the permanent magnetization decreases with time, but even over a period of 20×10^6 years the decrease is only about 40%.

b. Normally magnetized sediments have been studied. Their permanent magnetization has an intensity which is about one-hundredth of that of the lava flows (per cc.). This magnetization originated when the sediment was deposited; its direction is that of the local field.

c. The measurements show that taken over periods of several thousands of years the magnetic pole centres on the geographic pole. This has been so since Miocene times (approximately 20×10^6 years ago).

d. Reversely magnetized igneous and sedimentary rocks have also been found.

The reversely magnetized lava flows presumably occupy definite stratigraphic levels and can be traced as far as geological correlation permits. Zones of flows with normal and reverse magnetization alternate in comparable thicknesses. There are no significant differences in susceptibility and intensity of permanent magnetization between zones with normal and reverse magnetization. The large body of field evidence suggests that these zones are similar in every respect, except that they cooled down in fields of opposite directions but of similar strength. The same conclusion is indicated by the reversely magnetized sediments.

e. Of the four different mechanisms proposed by Néel which can produce reverse magnetization in a normal field, the two involving chemical action must be eliminated as they cannot be reconciled with the field evidence. On the other hand, the reverse magnetization of sediments (if acquired in a normal field) can only be explained by chemical action. The mechanism which assumes the interaction of two constituents of different Curie points, as well as the mechanism which appeals to the reversal of the direction of magnetization which occurs in certain types of ferrites when the temperature is suitably changed, can be shown by laboratory experiments not to be responsible for the natural reverse magnetization of the lava flows.

f. It is therefore suggested, though not without some reserve, that the Icelandic rocks have preserved a record of a repeatedly reversing main geomagnetic field. As the reversal is through 180°, it seems that this reversal is world-wide and is, in fact, a reversal of the polarity of the earth's magnetization. The manner in which the reversal takes place is still unknown, but it appears that the field changes ttheo opposite direction within one-fiftieth of the period over which a normal or a reversed field persists. The latter period is thought to be 250,000-500,000 years. The number of actually observed periods of reversed fields is 4, but the observations suggest that it is a recurrent phenomenon that has been taking place at least since Miocene times (approximately 20×10^6 years ago).

g. Within the limits of experimental accuracy Iceland has suffered no rotation and no changes in latitude since Miocene times. The position of the geographic poles in Miocene times as suggested by workers on polar wandering is definitely outside the possible range of positions and the theory of polar wandering is therefore not supported.

It is intended to publish a somewhat fuller account of the laboratory experiments on the origin of reverse magnetization of igneous rocks [4].

The possible use of the natural permanent magnetization of lava flows and other igneous rocks for correlation purposes has been considered in a separate paper [5]. Alternating zones of normal and reverse natural permanent magnetization, each comprising about 25 flows, have been found in the Tertiary and Quaternary plateau basalt series of Iceland. The techniques for measuring this permanent magnetization are discussed and prove to be extremely simple. Some results obtained in Iceland are shown. It is suggested that zones of normal and reverse

magnetization may be useful for correlation purposes in volcanic districts. Some other possible applications of rock magnetism for purposes of detailed correlation of individual lava flows and age determination are mentioned.

In collaboration with Mr. H.A.K. Charlesworth, University of Glasgow, the natural permanent magnetization of the so-called Lower Basalts of Northern Ireland, which are probably of Eocene age, has been studied [6]. It is found that all lava flows studied possess reverse magnetization, i.e., a magnetization approximately opposite to that of the present field.

The mean direction of magnetization of geologically speaking recent lava flows in Iceland, covering a period of several thousands of years, agrees closely with the direction of the theoretical dipole field (i.e., the field due to a geocentric axial dipole). This leads to the conclusion that, taken over a period of several thousands of years, the magnetic poles centre on the geographic poles. In the case of the Tertiary Northern Ireland lava flows it is found that the mean direction of magnetization is slightly different from the direction of the present dipole field but radically different from the direction of the dipole field calculated for the position of the geographic north pole in Eocene times as proposed by advocates of the polar wandering hypothesis. Though the former difference may conceivably be due to local geological processes, it may represent a real shift of the geographical pole.

This has led to a study of all available and suitable data on the directions of magnetization of Tertiary and Quaternary rocks, with a view to testing the polar wandering hypothesis [7, 8].

The mean direction of magnetization of series of recent lava flows and sediments has been determined. It is found that these mean directions agree closely with the theoretical dipole field (i.e., the field due to a geocentric axial magnetic dipole). The conclusion is therefore drawn that the mean position of the magnetic poles (taken over a period of several thousands of years) coincides with the geographic poles.

Assuming that the same is true for the geological past, the position of the geographic poles can be defined within fairly narrow limits by using the mean directions of magnetization of older rocks. The measurements used, published by various authors, comprise:

a. Early Quaternary lava flows from Iceland;
b. Plio-Pleistocene lava flows from France;
c. Mio-Pliocene lava flows from France;
d. Miocene lava flows from Iceland;
e. Oligocene or Miocene dykes from north England;
f. Oligocene igneous rocks from France;
g. Eocene lava flows from Scotland;
h. Eocene lava flows from Northern Ireland.

It is concluded that the large amount of polar wandering suggested by Kreichgauer, Köppen and Wegener, and Milankovitch cannot be reconciled with the new

data. If polar wandering has taken place at all, it has not exceeded 5–10° since Eocene times.

In this type of work on igneous rocks, one inevitably comes up against questions of age. The author's reasons for considering part of the Icelandic lava flows (plateau basalts) as of Tertiary age, and another part of these as of Early Quaternary age (the latter have glacial beds between them) have been set forth in a separate paper [9]. An abstract and discussion of this paper will be found in the Proceedings of the Geological Society of London [10].

References

[1] J. Hospers, Remanent magnetism of rocks and the history of the geomagnetic field. Nature, vol. **168**, pp. 1111–2, 1951

[2] „ Palaeomagnetic studies of igneous rocks. Ph. D. Thesis, Cambridge University, 1953.

[3] „ Reversals of the main geomagnetic field, I–III. Proc. Kon. Ned. Akad. Wet., **B**, vol. **56**, pp. 467–491, 1953 and vol. **57**, pp. 112–121, 1954.

[4] „ Origin of the reverse magnetization of Icelandic lava flows (in preparation).

[5] „ Magnetic correlation in volcanic districts. Geological Magazine, vol. XCI, pp. 352–360, 1954.

[6] „ and H.A.K. Charlesworth, The natural permanent magnetization of the Lower Basalts of Northern Ireland. Mont. Not. Roy. Astr. Soc., Geophys. Suppl., vol. **7**, pp. 32–43, 1954.

[7] „ Rock magnetism and polar wandering (summary of (8)). Nature, vol. **173**, pp. 1183–1184, 1954.

[8] „ Rock magnetism and polar wandering. The Journal of Geology (in the press).

[9] „ The geology of the country between Akureyri and Myvatn in northern Iceland. Geologie en Mijnbouw (Journal of the Royal Netherlands Geological and Mining Society), (nw. ser.), vol. **16**, pp. 491–508, 1954.

[10] Proceedings of the Geological Society of London, No. **1505**, 25 January 1954, pp. XXIII–XXVII.

Correlation of Reverse Remanent Magnetism and Negative Anomalies with Certain Minerals*

By J. R. BALSLEY and A. F. BUDDINGTON

U.S. Geological Survey, Washington, D.C. and Princeton, N.J.

The U.S. Geological Survey has been investigating negative anomalies discovered by aeromagnetic surveys in the Adirondack Mountains, New York; Upper Peninsula, Michigan; Bearpaw Mountains, Montana; Fairfax County, Virginia; Aroostook County, Maine; and northern New Jersey. The rocks producing the anomalies are igneous or metamorphic, range in age from pre-Cambrian to Triassic, and all have reverse remanent magnetization.

The nature and origin of this magnetization are now being studied and this report must be considered preliminary. However, the investigations have already yielded information of considerable importance in palaeomagnetism. More than 200 oriented specimens of a series of varied igneous rocks and equivalent gneisses and intensely metamorphosed and modified sediments, all of pre-Cambrian age, have been collected in the Adirondack Mountains, and the chemical and mineralogic composition and the magnetic susceptibility and remanent magnetization of the specimens have been determined. We are indebted to J.J. Fahey and A.C. Vlisidis for all the chemical data and to L.A. Anderson for many of the magnetic measurements.

The rocks can be separated into three groups, those which have normal magnetization, those which have reverse magnetization, and those which have magnetization intermediate between these extremes. The chemical and mineralogical analysis of the rocks indicates that the accessory minerals of each group have characteristic composition and leads to the conclusion that there is a close relationship between the composition and the magnetic properties of this suite of rocks. This is shown in Fig. 1. The data incorporated in this diagram are not corrected for local distortions of the earth's magnetic field produced by geologic features such as magnetite ore bodies, or for the effects of lightning, magnetostriction or other factors which might affect the magnetization of the rocks. The surprisingly few inconsistent data in the general pattern of the diagram are all from rocks which are found as thin layers in large masses of rock with consistent properties. Although it has not yet been shown it is likely that their magnetization has been produced or altered by one of the factors mentioned above.

---

* Publication authorized by the Director, U.S. Geological Survey.

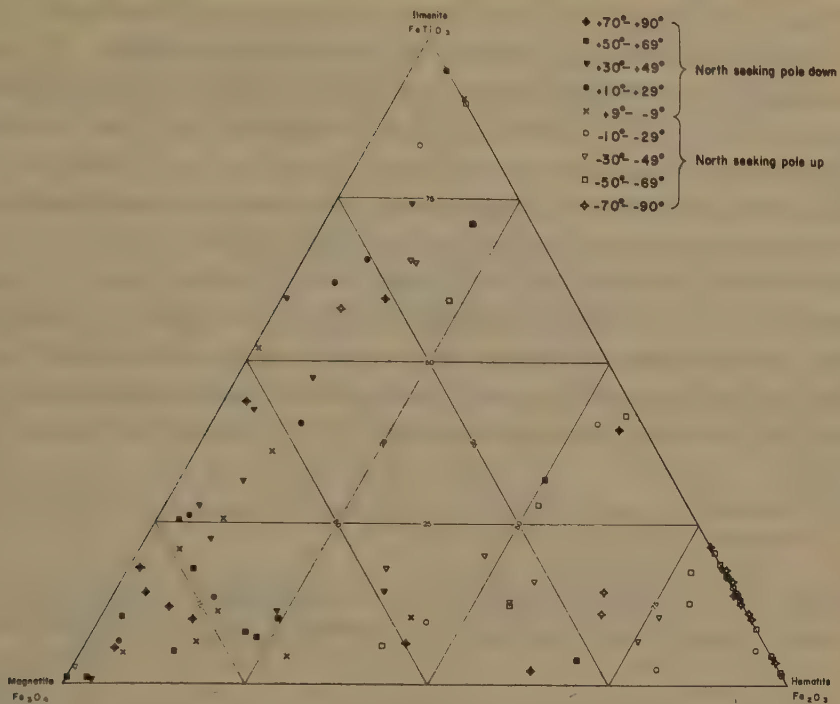


Fig. 1 Variation of magnetic properties with variation of composition of iron-titanium oxides.

In one group the accessory oxide minerals consist exclusively of members of the magnetite (Fe_3O_4)—ilmenite ($FeO \cdot TiO_2$)—ulvöspinel ($2FeO \cdot TiO_2$) series and the magnetic properties are normal, that is, the remanent magnetization is in the direction of the earth's field and the ratio of remanent to induced magnetization is about 1 or less than 1. The primary accessory oxide is ilmenomagnetite (magnetite with exsolved intergrowths of ilmenite) and, in some specimens, ulvöspinel. The ilmenite intergrowth is visible at moderate magnifications, but the ulvöspinel is commonly an ultrafine intergrowth in the magnetite and visible only at high (several hundred or more) magnifications. The titaniferous magnetite is accompanied by separate independent grains of ilmenite similar in size to the magnetite.

In a second group of rocks the accessory oxide minerals are exclusively members of the hematite (Fe_3O_3)—ilmenite ($FeO \cdot TiO_2$)—rutile (TiO_2) series and the rocks uniformly show reverse remanent magnetism and give rise to negative anomalies. The accessory oxides may be titanhematite (Fe_2O_3 with as much as 10 percent TiO_2 in solid solution as $FeO \cdot TiO_2$ and as TiO_2), ilmenohematite (titanhematite with exsolved microintergrowths of ilmenite), rutilohematite (titanhematite with exsolved microintergrowths of rutile), ferricilmenite ($FeO \cdot TiO_2$ with as much as 13 percent Fe_2O_3 in solid solution), or hemoilmenite (ferricilmenite with exsolved microintergrowths of titanhematite or ilmenohematite). Titanhematite, ferricilmenite, ilmenohematite, and rutilohematite may each occur as the only accessory oxide in the

rock. Ilmenohematite and hemoilmenite may occur as independent grains or as coarse intergrowths in the same rock. Rocks in this group characteristically have high coercivity and a high ratio of remanent to induced magnetization. In rocks in which titanhematite is the only accessory oxide the coercivity is greater than 2000 gauss and the ratio of remanent to induced magnetization is as high as 1700. Rocks containing pure hematite or pure ilmenite have not been found, but a few containing nearly pure minerals suggest that the remanent magnetization of the hematite and ilmenite may be in the direction of the earth's field.

The accessory oxides of the third group of rocks are mixtures of magnetite and members of the hematite-ilmenite-rutile series. The magnetic properties are transitional between those of the first two groups of rocks with normal remanent magnetism for the grains of magnetite and reverse remanent magnetism for the members of the hematite-ilmenite-rutile series. This is shown in Tables 1 and 2.

*Table 1. Variations of magnetic properties with variation in ratio of Fe_3O_4 to Fe-Ti Oxides, Magnetite-Titanhematite Series.**

No. Specimens		Wt. Fe-Ti Oxides	Chemical analyses of Fe-Ti oxides recomputed				Remanent Magnetism		Susceptibility cgs $\times 10^{-3}$	Mineralogy
			Fe_3O_4	Fe_2O_3	$FeO \cdot TiO_2$	TiO_2	Intensity $\times 10^{-3}$	Inclination		
7	Av.	4.5	76.8	11.9	8.0	3.2	1.17	+55°	4.69	Magnetite (Ilmeno-hematite & Hemo-ilmenite)
	Range	1.52-6.65	66-89	4.5-21.6	5.4-11.8	1.3-6.5	0.35-2.16	+18°-+86°	2.13-8.97	
4	Av.	4.27	49.3	36.3	10.2	4.1	2.3	−14°	2.22	Magnetite Ilmeno-hematite
	Range	2.19-7.27	41.4-66.0	28.0-45.2	4.5-16.3	1.5-10.9	1.0-4.5	+3°-−32°	1.00-4.17	
5	Av.	5.82	26.1	55.1	14.0	4.8	3.4	−48°	1.94	Ilmeno-hematite (Magnetite)
	Range	2.15-11.38	11.9-31.0	46.0-71.1	10.2-19.1	2.4-6.8	1.8-5.7	−41°-−57°	0.56-4.54	
5	Av.	6.76	1.4	80.1	14.3	4.1	3.9	−64°	0.51	Titanhematite with meagre ilmenite & rutile intergrowth
	Range	5.00-9.66	0-7.2	76.6-84.9	12.6-17.1	0.3-10.3	3.7-4.1	−62-−67°	0.012-0.154	
10	Av.	5.66	0.5	78.0	16.5	5.1	6.8	−67°	0.031	Titanhematite with ilmenite and rutile intergrowth
	Range	3.92-11.54	0-4.8	74.5-85.4	13.3-20.0	1.3-8.4	2.6-13.7	−60-−73	0.004-0.222	
4	Av.	4.75	0.0	88.0	4.8	7.3	1.43	−67°	0.011	Rutilo-hematite
	Range	1.59-6.67		82.8-91.9	2.0-10.5	5.5-10.8	0.16-3.30	−56-−73°	0.006-0.014	
1**		44.7	0.2	96.8	2.3	0.7	0.30	+55°	1.46	Hematite

* The rocks are exclusively microcline-rich quartz gneiss produced by granitization of pre-Cambrian Grenville sediments. Most of the rocks contain sillimanite.

** Not plotted on triangular diagram because contains abnormally high percentage of oxide.

*Table 2. Variations of magnetic properties with variation in ratio of Fe_3O_4 to Fe-Ti Oxides. Magnetite-Ferricilmenite Series.**

No. Specimens		Wt. Fe-Ti Oxides	Chemical analyses of Fe-Ti oxides recomputed				Remanent Magnetism		Susceptibility cgs $\times 10^{-3}$	Mineralogy
			Fe_3O_4	Fe_3O_4	$FeO \cdot TiO_2$	TiO_2	Intensity $\times 10^{-3}$	Inclination		
4	Av.	5.01	74.0	11.4	11.2	3.4	0.43	+75°	3.01	Magnetite (Ilmenohematite & hemo-ilmenite or Ferricilmenite)
	Range	2.08-6.65	68.6-77.3	8.5-13.1	10.1-11.8	1.3-6.5	0.37-0.56	+61°-+86°	0.92-4.87	
7	Av.	4.05	66.4	7.4	27.1	0.7	1.02	+44°	4.16	Ilmenomagnetite and Ferricilmenite
	Range	0.94-10.33	59.0-73	4.5-9.0	22.3-31.6	0.2-1.2	0.17-4.52	+31°-+61°	0.54-18.0	
4	Av.	2.81	37.1	8.1	52.3	2.5	0.38	+17°	1.54	Ilmenomagnetite and Ferricilmenite
	Range	1.17-5.83	25.9-51.2	5.8-10.2	35.0-65.4	0.0-3.8	0.11-0.55	+9°-+25°	0.53-2.59	
10	Av.	1.37	12.6	13.1	68.8	5.5	0.36	−61°	0.368	Ferricilmenite (Ilmenomagnetites, little rutile)
	Range	0.48-4.28	0-27.1	7.0-21.3	54.0-87.6	2.6-7.8	0.10-0.89	−48°-−77°	0.032-2.22	
1		11.68	0.2	4.8	93.5	1.5	0.17	+69°	0.20	Ilmenite

* The rocks predominantly hornblende microperthite granite or equivalent hornblende microcline-oligoclase gneiss. A few are pyroxene diorite, gabbroic anorthosite or equivalent gneiss.

It is dfficult to explain the reverse magnetization of the rocks of the second group by assuming that they cooled through the Curie point at a time when the earth's field was reversed. These rocks include sillimanitic or pyroxenic microcline-quartz gneisses representing granitized metasediment, hornblende and biotite metasedimentary gneiss, pyroxene granitic gneiss, hornblende granite, anorthosite, and such titaniferous hematite ore bodies as that in anorthosite at Allard Lake, Quebec and part of that in quartz-microcline gneiss at Benson Mines, N. Y. They are found in masses as much as a few thousands of feet wide and a few miles long distributed throughout an area of more than 3,000 square miles. The rocks are all of different ages and it is unlikely that these several periods of formation of members of the hematite-ilmenite-rutile series should each time coincide with a period when the earth's field was reversed. These rocks are metamorphic, and it is therefore possible that all have been reheated above the Curie point and then recooled during a period when the earth's field was reversed; but if this were so the oxides of the magnetite-ilmenite-ulvöspinel series in adjoining rocks should also exhibit inverse magnetization, which they do not. It has been suggested that the magnetite-ilmenite-ulvöspinel oxides were reversely magnetized and because of their relatively lower coercivity have lost the reverse magnetization which was retained by the highly coercive hematite-ilmenite-rutile oxides. There is no direct evidence to support or disprove this suggestion, but the extremely high ratio of remanent magnetization to induced magnetization of the rocks containing the hematite-ilmenite-rutile oxides makes it seem unlikely that they could have been magnetized

in the normal manner in a reversed earth's field unless the intensity of the field were at least several hundred times the present field. As there is no evidence or suggestion that the earth's field has attained this high intensity and, particularly, that it should have such an intensity each time the hematite-ilmenite-rutile oxides formed, one must search for other means to explain the peculiar magnetization of these rocks.

Our tentative conclusion is that the reverse remanent magnetization of these rocks is the result of the action of the normal earth's field on the inherent properties of the grains of intimately mixed hematite and ilmenite which they contain. This conclusion has been verified by heating above the Curie point one specimen containing the hematite-ilmenite mixture and cooling it in the earth's field. It was found to posses remanent magnetization opposite to that of the impressed field. Nagata [1] has also observed this phenomenon in Japanese rocks with accessory oxides of this composition.

The mechanism by which the oxide grains become magnetized in a direction opposite to that of the impressed field has not yet been demonstrated. Néel [2] has proposed two methods by which this could occur: one, involving an N- or V-type ferrite, and the other involving a compact mixture of two materials with different Curie points. In the first case the molecular structure of the ferrite is such that "when the coefficients of the molecular field have appropriate values, the sign of the spontaneous magnetization changes with increasing temperature." In the second case the material "with the lower Curie point may be magnetized opposite to the externally applied field by action of the demagnetizing field due to the other constituent." [3] The latter seems the most probable explanation of the reverse remanent magnetization of the Adirondack rocks. The high coercivity of the rocks exhibiting the most pronounced reverse remanent magnetization and their high ratio of remanent to induced magnetization lead us to conclude that the second component of the Néel two-phase system must occur in separated particles of domain size distributed through the first component. Thus the slight demagnetizing field set up by the first component acts only to direct the spontaneous magnetization of the individual, isolated single domains of the second component. Thus the intensity of magnetization is a function of the spontaneous magnetization of the second component and its quantity and is essentially independent of the intensity of the external field. The coercivity of such a system would of course be extremely high. An attempt has been made to prove this conclusion by heating specimens above the Curie point and cooling in known fields, but unfortunately the structure of these complex grains has apparently been changed in the process even though the experiments have been conducted at pressures less than 10 microns Hg. Because the particles of the second component are small they are readily dissolved at moderately low temperatures in the first component and during the period of cooling in a normal experiment they do not have sufficient time to exsolve.

These tentative conclusions are now being tested by experimental heating at

different rates of rocks and minerals of known chemical and mineralogic composition, by X-ray and electron-microscope studies and studies of domain structures.

References

[1] Nagata, Takesi, Self-reversal of thermo-remanent magnetization of igneous rocks: Nature, vol. 172, no. 4384, pp. 850-852, (1953).

[2] Néel, Louis, L'inversion de l'aimantation permanente des roches (The inversion of the permanent magnetization of rocks): Annales Géophys., tome 7, no. 2, pp. 90-102, (1951).

[3] Néel, Louis, op. cit. 90.

Reverse Magnetization of Rocks and Its Connection with the Geomagnetic Field

By T. NAGATA, S. AKIMOTO and S. UYEDA
Geophysical Institute, Tokyo University

and

K. MOMOSE and E. ASAMI
Sinsyu University Yamaguti University

Abstract

From the present knowledge on the magnetism of rocks, palaeomagnetic study by means of the natural remanent magnetization of igneous rocks is reliable when and only when the natural remanent magnetization is ascertained to be the thermo-remanent magnetization acquired at the time of the rocks' formation. The authors propose, in this paper, several experimental methods for examining whether a given natural remanent magnetization can have definite palaeomagnetic significance or not, under the above mentioned criterion.

In short, the proposed set of testing methods comprises: thermo-magnetic, crystallographic and chemical analyses of the ferromagnetic minerals contained in the rock, and the comparison of the stabilities of the natural remanent magnetization and of the thermo-remanent magnetization, produced in laboratory, against the demagnetizing processes by heating in non-magnetic space and by applying an alternating magnetic field.

These proposed tests were actually carried out on several naturally adversely magnetized rocks found mainly in Japan. For three of them, including Dr. Hospers' Icelandic rock, it was concluded that their reverse natural remanence must have been brought about by the reversed earth's magnetic field at the times of their formation.

As to the Haruna type of the self-reversal of the thermo-remanent magnetization, the two-constituent mechanism was investigated in detail with the aid of electron-microscopic observation on the intergrowth of the two constituents.

§ 1. Reliability of NRM of igneous rocks for palaeomagnetic purposes.

If it is proved that reversely magnetized igneous rocks have kept their natural remanent magnetization (NRM) stable since they acquired it as thermo-remanent magnetization (TRM) under the effect of the geomagnetic field in remote epochs, we must conclude that the geomagnetic field at the time of formation of these rocks was reversed in comparison with the present field. Therefore the most important problem in palaeomagnetic studies on rock magnetism at present is examining whether or not the reverse NRM of rocks found *in situ* is really due to the TRM which was produced while these rocks were cooled down, and whether or not it has been much disturbed since it was produced. It may be stated at present that the TRM of stable ferromagnetic minerals only is able to remain stable during a long geologic period.

Our studies on the reverse NRM of igneous rocks in Japan have been carried out along the above-mentioned lines. Basic elements of our examination of the NRM of igneous rocks are as follows:

(a) $\bar{D}$ and $\bar{I}$: Mean values of the declination and the inclination of the NRM of rock specimens *in situ*.

(b) J_n: Specific intensity of NRM.

(c) J_{Tc}: Specific intensity of the total TRM, (*i. e.* TRM obtained by cooling from a temperature above the highest Curie point to the atmospheric temperature), in the present geomagnetic field.

(d) $(J_n)_T$: Specific intensity of the NRM of a specimen after demagnetization by heating up to T and then cooling down in non-magnetic space. $(J_n)_T$ is given as a function of T when T is successively increased, and this relation represents the mode of diminishing of J_n with increase in T.

(e) $(J_{Tc})_T$: Specific intensity of the total TRM of a specimen after demagnetization by heating up to T and then cooling down in non-magnetic space.

(f) $J_s(T)$: Specific intensity of the saturation magnetization as a function of temperature.

(g) $(J_n)_{\tilde{H}}$: Specific intensity of the NRM of a specimen after demagnetization by an alternating magnetic field $\tilde{H}$, where $\tilde{H}$ denoting the maximum amplitude of the applied alternating magnetic field.

(h) $(J_{Tc})_{\tilde{H}}$: Specific intensity of the TRM of a specimen after demagnetization by an alternating magnetic field $\tilde{H}$.

(i) Crystal structure of the ferromagnetic minerals separated from a rock specimen: This is determined by X-ray analysis before and after the heat-treatment.

The measurements of $J_s(T)$ were carried out in high vacuum, while the heat-

treatments for $(J_n)_T$ and $(J_{Tc})_T$ were generally made in the atmosphere except for several cases where the effect of oxidation seemed not negligible.

The results of measuring these elements were applied for criticizing the possibility of attributing the NRM to the TRM and the stability of remanent magnetization, with the aid of criteria mentioned in the following:

1) If J_{Tc} of a rock specimen is negative, *i.e.* if the TRM is reversed compared with the direction of the applied magnetic field, it is highly probable that the NRM of the rock is due to the self-reversal of TRM.

2) If the value of J_n/J_{Tc} of a rock specimen is nearly equal to unity, or not much less, and further if the mode of the $(J_n)_T$ curve is fairly similar to that of the $(J_{Tc})_T$ curve, we may conclude that the NRM of the rock is attributable to the TRM of the same sample and that the direction of the NRM which was produced as the TRM in a remote epoch has remained without appreciable change during a long time. It is because magnetic properties of the rock responsible for the NRM seem to keep sufficiently stable during this long period except for an inevitable decay of a small amount of its intensity owing to the so-called magnetic after-effect.

3) If alternatively the $(J_n)_T$ curve is appreciably different from the $(J_{Tc})_T$ curve of the same rock specimen, the NRM is not directly attributable to the TRM which is approximately reproducible in the laboratory, and a doubt will arise whether the NRM has been appreciably changed *in situ* during a long period. The magnetic properties of such specimens must be carefully examined in order to find the cause of the observed NRM. Sometimes, however, ferromagnetic minerals in rocks are unstable, their magnetic properties being changed by heat-treatments, especially in the atmosphere. This change can be detected directly by crystallographic analyses of the ferromagnetic minerals before and after the heat-treatment and also by measuring the $J_s(T)$ curve repeatedly. (See § 2). Such change is mainly due to oxidation, and therefore in a high vacuum (say, the air pressure $< 10^{-3}$ mmHg), repeated heat-treatments of such samples up to about 600°C do not much alter their magnetic properties in most cases.

4) If the $(J_n)_T$ curve is still different from the $(J_{Tc})_T$ curve in the high vacuum, we may presume that (i) the NRM is due to thermally unstable ferromagnetic minerals, or (ii) it is caused by other processes than the TRM phenomenon, or (iii) the NRM cannot be reproduced owing to changes in ferromagnetic minerals during a long time. At any rate the NRM in such cases must be avoided for the purpose of palaeomagnetism.

5) If the NRM is due to the isothermal remanent magnetism at the atmospheric temperature, this comparatively unstable magnetization can easily be demagnetized by applying an alternating magnetic field, because the coercivity of isothermal remanent magnetization is much less than that of the TRM. Consequently, the $(J_n)_{\tilde{H}}$ curve of a specimen should be compared with its $(J_{Tc})_{\tilde{H}}$ curve and the A.C. field demagnetization curve of the isothermal remanent magnetism (IRM), produced in laboratory, of which intensity being adjusted to have the same order of magnitude

with the J_n. If the $(J_n)_{\tilde{H}}$ curve is much different from the $(J_{Tr})_{\tilde{H}}$ curve and resembles to the A.C. field demagnetization curve of the IRM, this NRM can be attributed to the IRM with certainty. The NRM which is attributable to the IRM must be excluded from the objects of palaeomagnetic studies. When the $(J_n)_{\tilde{H}}$ curve is similar to neither of the $(J_{Tr})_{\tilde{H}}$ curve and the A.C. field demagnetization curve of the IRM, the non-identity of the J_n and the J_{Tr} is still obviously valid and such NRM should also be excluded from the palaeomagnetic use.

The difference in the coercivity between the TRM and the IRM is well illustrated in Fig. 1. In Fig. 1. the full circles represent the A,C. field demagnetization curve for the Gembudô sample (See 2.) that posesses the TRM and the IRM superposed in the same direction. That the A.C. field demagnetization of the IRM is nearly perfected by $\tilde{H}$ of 80 *Oe.* while that of the TRM is still on its midway by $\tilde{H}$ of 360 *Oe.* will be clearly seen. In the case of the hollow circles, on the other hand, the comparatively intense IRM is superposed in the direction opposite to that of the TRM, so that the resultant remanent magnetization is oriented adversely to the direction of the latter at the beginning of the demagnetization process. Since the IRM is demagnetized by the A.C. field less than 100 *Oe.*, which keeps the TRM almost intact, a reversal in the resultant remanence takes place. When the anomalous NRM has some IRM-origin, such as the IRM caused by the locally intense magnetic field of the thunderbolts, the A.C. field demagnetization test should thus be able to detect it out.

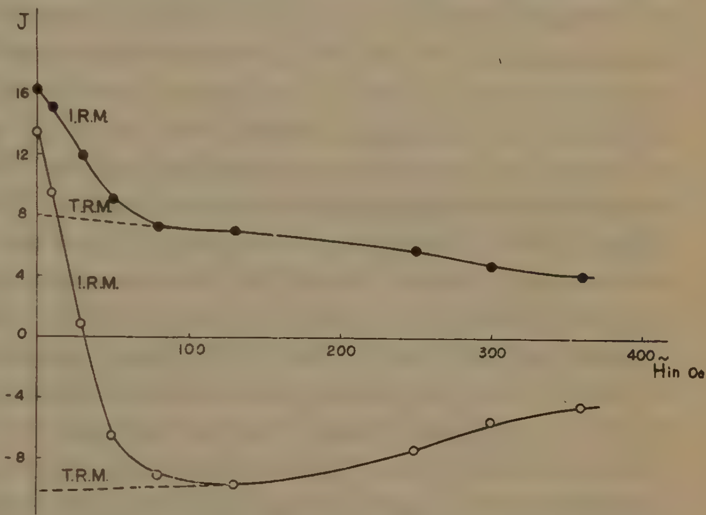


Fig. 1 Demagnetization curve by alternating magnetic field.
Full circles: TRM and IRM superposed in parallel direction.
Hollow circles: TRM and IRM superposed in anti-parallel direction.
sample: Gembudô basalt.

6) In conclusion, the NRM of rocks having the following characteristics can be used as a reliable indicator of the direction of the geomagnetic field in remote epochs.

i) The $(J_n)_T$ curve is similar to the $(J_{Tr})_T$ curve in their modes as well as in their intensities.

ii) Curie point is not much less than 580°C, *i.e.* the ferromagnetic minerals responsible for the NRM are mainly Ti-poor titanomagnetite.

iii) The coercivity of the NRM is sufficiently large, being nearly identical to

that of the TRM.

§ 2. Actual test of NRM of reversely magnetized igneous rocks.

The test of reliability of the NRM mentioned above was applied for examining four typical groups of reversely magnetized rocks in Japan, *i.e.* Gembudô basaltic lava, Kawaziri-Misaki basaltic lava, Suwa andesitic lava and Haruna dacitic pumice. In comparison, 6 samples of Icelandic lava offered by Dr. J. Hospers were also examined. The main results are summarized in the attached table.

(1) *Gembudô basalt.*

The revese NRM of Gembudô basalt has been known since its discovery by M. Matuyama [1] in 1927. It has recently been found that a similar lava nearby has a rather normal NRM. As shown in the table, the $(J_n)_T$ curve obtained in the atmosphere is appreciably different from the $(J_{Tr})_T$ curve in both the reversely magnetized rock and the normally magnetized one. It was confirmed by measuring the $J_s(T)$ curve in the atmosphere and in vacuum and by X-ray analysis before and after the heat-treatment in the atmosphere that the change is due to change of ferromagnetic minerals from Ti-rich titanomagnetite having a low Curie point to Ti-poor titanomagnetite having a high Curie point. The Curie point of the original ferromagnetic minerals is about 120 C, suggesting that magnetization of these rocks is apt to be also magnetically disturbed in the atmospheric temperature. Besides, the A.C. field demagnetization tests also show that the curves of $(J_n)_{\tilde{H}}$ and $(J_{Tr})_{\tilde{H}}$ are significantly different in both the reverse and the normal NRM samples. Consequently it will be safe to exclude the Gembudô rocks from the present palaeomagnetic study, though it seems that their unusual character well deserves detailed examination.

(2) *Kawaziri-Misaki basalt.*

Basaltic lavas at Kawaziri-Misaki have reverse NRM, while the similar lavas nearby have normal NRM, their intensity ranging from 10^{-4} to 10^{-2} emu/gr. in order [2]. Typical specimens of each group of the reversely magnetized rocks and the normally magnetized ones were examined. In both cases, the $(J_n)_T$ curve is very similar to the $(J_{Tr})_T$ curve and the latter is a very typical $(J_{Tr})_T$ curve of Ti-poor titanomagnetite grains. According to the results of the A.C. field demagnetization tests, the NRM of the Kawaziri-Misaki basalt is proved to be not more unstable than the TRM in both cases of the reverse and the normal NRM. In the rocks having relatively strong NRM, the value of J_n/J_{Tr} is approximately unity, while it is small in the rocks having weak NRM, suggesting that the magnetization in the latter case has been much reduced in a long time. The $J_s(T)$ curve and the result of the X-ray analysis indicate that the main ferromagnetic constituent in all Kawaziri-Misaki rocks is Ti-poor titanomagnetite, but there is also a small amount of hematite or hematite-ilmenite solid solution. Thus there is very little room for doubt that the NRM of the Kawaziri-Misaki basalt is mainly due to the TRM, and the reverse NRM would be caused by the reversed geomagnetic field. Unfortunately, however,

it is difficult to determine the geological relation between the reversely magnetized lava and the normally magnetized lava in this place.

(3) *Andesitic lava at Suwa.*

All samples taken from the andesitic lava at a quarry in Suwa are reversely magnetized. Their $(J_n)_T$ curve is quite similar to the $(J_{T.c})_T$ curve, the former being about 0.6 times the latter in intensity. These $(J_n)_T$ and $(J_{T.c})_T$ curves are very normal, being undoubtedly attributable to those of the grains of Ti-poor titanomagnetite. This conclusion is also supported by the $J_s(T)$ curve and the X-ray data. The results of the A.C. field demagnetization tests can be regarded as passable, though the decrease of the NRM is somewhat more appreciable than that of the TRM. There will be no other interpretation of this reverse NRM than assuming the reversed geomagnetic field.

(4) *Haruna dacite pumice.*

The layer of dacitic pumices of Mt. Haruna is reversely magnetized. The $(J_n)_T$ and the $(J_{T.c})_T$ curves of these pumices are very similar to each other, but both of them show a distinct self-reversal with an increase in temperature [3]. The $(J_n)_{\tilde{H}}$ curve and the $(J_{T.c})_{\tilde{H}}$ curves are fairly similar, indicating that the NRM can be attributed to the TRM. As indicated by the $J_s(T)$ curves and the X-ray data, the ferromagnetic minerals in these rocks consist of Ti-poor titanomagnetite and ferromagnetic solid solutions between ilmenite and hematite [4]. According to the data of the $J_s(T)$ tests, the both components are fairly stable against the heating up to the highest Curie point of them. It was verified that magnetic coupling between two different ferromagnetic constituents result in the self-reversal of TRM of these rocks. There will be no doubt that the reverse NRM of the Haruna rocks is due to the self-reversal of TRM.

(5) *Iceland basaltic lava.*

Six samples of Icelandic basaltic lava which was studied in detail by J. Hospers [5] were also examind with the method dealt with here. As shown in the attached table, some of the normally magnetized rocks are not perfectly free of ambiguity as to the stability of their ferromagnetic minerals, but the reversely magnetized rocks are very normal, their reverse NRM being attributable to the TRM produced in the reversed geomagnetic field.

Summarizing all results described above, we may conclude that there is no evidence for doubting that the direction of the geomagnetic field, which influenced the production of the reverse NRM of the Suwa andesite, the Icelandic basalt and probably the Kawaziri-Misaki basalt, was nearly opposite to that of the present field.

§ 3. Two-constituent structure of ferromagnetic mineral and reverse magnetization.

The possibility of the self-reversal of TRM in ferromagnetic minerals containing two different constituents was pointed out by L. Néel [6], and its real existence was proved in the Haruna dacitic pumice [3]. Similar examples were also found in Adirondack in U.S.A. by J.R. Balsley and A.F. Buddington [7], although the

Table. 1

Locality	Grain	Crystal Structure	Lattice Parameters	Curie Point
Haruna	A	Cubic	$a=8.403\pm0.002$ Å	460°C
	B	Rhombohedral	$a_{rh}=5.480\pm0.002$ Å, $\alpha_{rh}=55°05'\pm01'$	250
Asio	A	Cubic	$a=8.397\pm0.004$ Å	460
	B	Rhombohedral	$a_{rh}=5.483\pm0.004$ Å, $\alpha_{rh}=55°02'\pm03'$	230
Towada	A	Cubic	$a=8.412\pm0.003$ Å	390
	B	Rhombohedral	$a_{rh}=5.491\pm0.001$ Å, $\alpha_{rh}=54°59'\pm01'$	100

participating ferromagnetic minerals seem to be different from the Haruna case. The mechanism of the self-reversal of TRM in Haruna rocks has been examined in fair detail [8]. The two constituents are (A) supposedly titanomagnetite and (B) ferromagnetic solid solution of ilmenite-hematite, and the interaction between them takes place actually as magnetic interaction between individual domain-scale units of these constituents within one grain. This means that the actual mechanism of the interaction is somewhat different from that in Néel's original proposal.

It is true that the presence of these two different magnetic constituents, A and B, in rocks does not always result in the self-reversal of the TRM. As shown in the following table, ferromagnetic minerals of dacites at Haruna, Asio and Towada are composed of similar constituents, their $J_s(T)$ curves well resembling each other. As already reported, the total TRM of the Haruna rocks is reverse, but the total TRM of the majority of the Asio rocks is normal at the atmospheric temperature, though there is also a distinct tendency of reversed magnetization of the B constituent in the latter. In the Towada rocks, the total TRM is perfectly normal, the direction of TRM of the B constituent being parallel to that of the A constituent. The said characteristics in the three types will be clearly illustrated in Fig. 2, which represents schematically the $(J_{Tc})_T$ curves in the three cases. The magnetic interaction between A and B is the strongest in the Haruna rocks and the weakest in the Towada rocks, where it is practically negligible. Thus it may be concluded that the self-reversal of TRM owing to the two-constituent mechanism can take place in rocks only under a particular condition that the ferromagnetic minerals consist

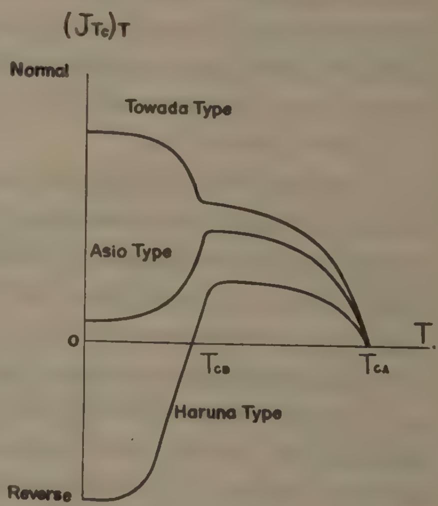


Fig. 2 Schematic diagram of $(J_{Tc})_T$ curves of rocks having two-constituent structure.
T_{cA} : Critical temperature for fixing magnetization of the A constituent.
T_{cB} : Critical temperature for fixing magnetization of the B constituent.

of the A and B constituents and further that they are closely coupled in domain scale. In Japan, so far, other rocks having the similar composition of ferromagnetic minerals have been found [9], and complete reversal of TRM like in the Haruna case was discovered in none of them, only one of them having the partially reversed TRM as in the Asio rock [10] and all of the rest belonging to the Towada type.

Fig. 3 is an electron-micrograph of the polished surface of the ferromagnetic grain of the Haruna sample having the RTRM characteristics [11].

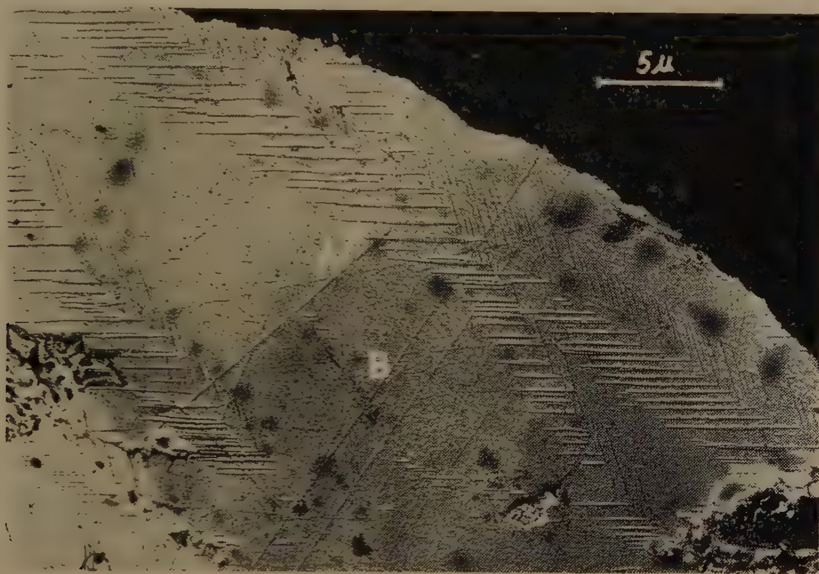


Fig. 3 Electron-micrograph of the intergrowth of A in echelon into B in Haruna ferromagnetic minerals.

The polished surfaces of the minerals were etched by HCl during 15 minutes: parts of the A constituent (supposedly of titanomagnetite phase) can be etched easily while parts of the B constituent is scarcely done. In this figure, it is clearly seen that A constituent intergrows in echelon into the matrix of the B constituent. The approximate width and the length of the observed strips are 0.2μ and few microns. Although the detailed calculation is not reproduced here, its results showed that the magnetic interaction between the A and the B strips seen in the micrograph may be able to cause the self-reversal of TRM.

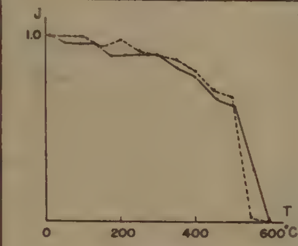
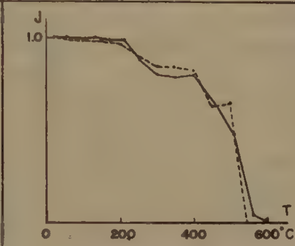
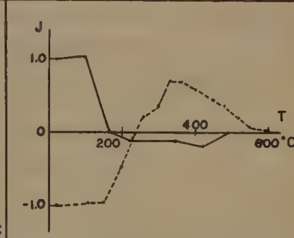
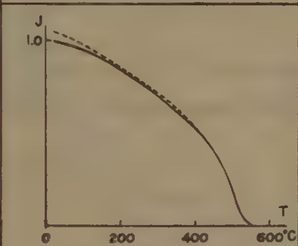
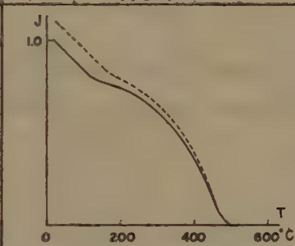
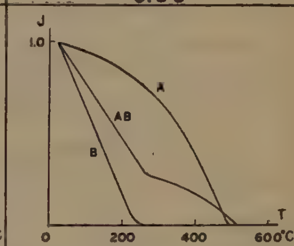
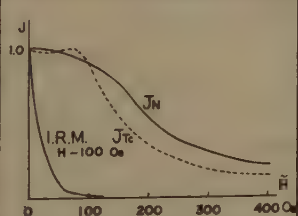
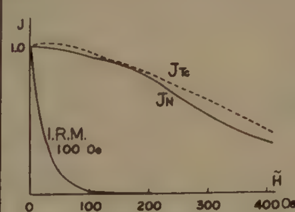
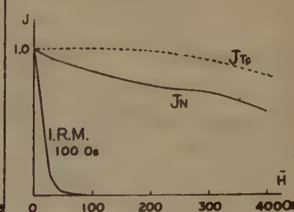
Whether this finely intergrown A constituent consists of the titanomagnetite or of the ilmenite-hematite phase or of some other material such as pyrrhotite, with higher Curie point than the host, is not very much clear, because the above mentioned difference in the degree of etching is not regarded to be a very confirming measure for the determination of phase in comparison with, for instance, the crystallographic method. In fact, the existence of the Ti-poor titanomagnetite in the grains having the RTRM characteristics proved by the $J_s(T)$ curves [4], [8] might have merely been of some coarsely coexisting titanomagnetite phase, and not of the fine lamellae. The more reliable identification of the phase of these lamellae

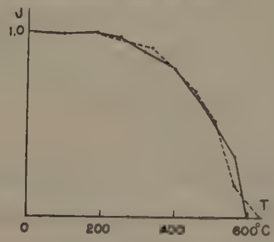
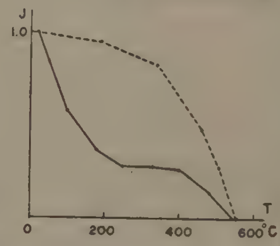
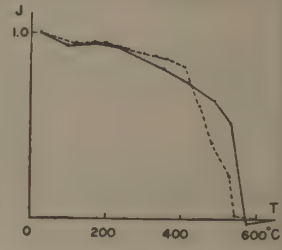
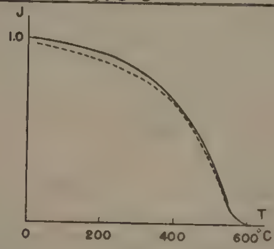
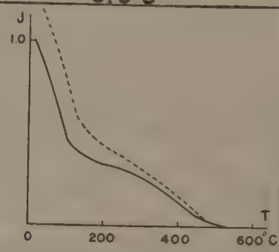
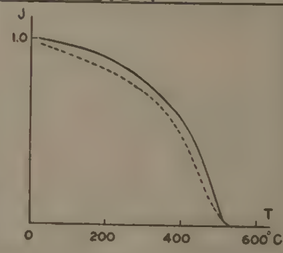
is now being made.

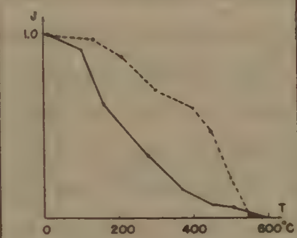
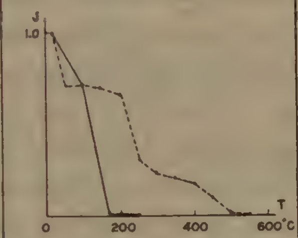
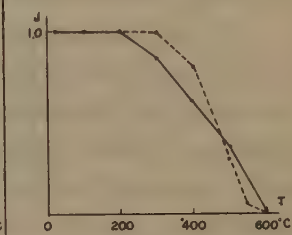
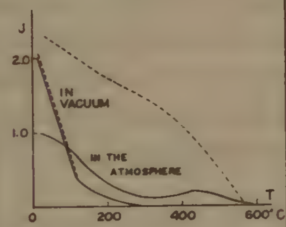
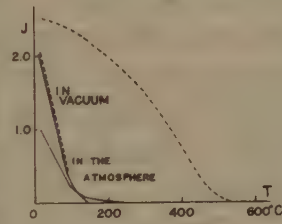
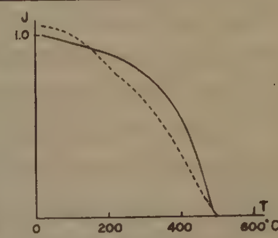
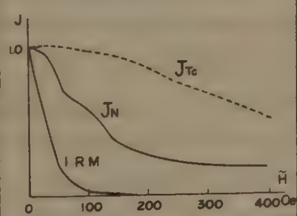
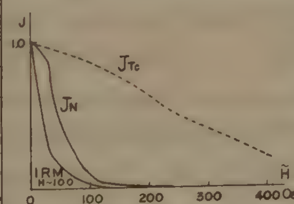
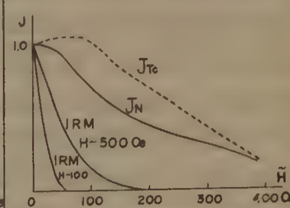
It will be quite desirable to extend this sort of detailed study of the problem of the magnetic interaction between different phases in ferromagnetic minerals from the very exceptional Haruna case to the more general ones.

References

[1] M. Matuyama, Proc. Imp. Acad. of Japan, **5**, 203 (1929).
[2] E. Asami, Proc. Japan Acad., **30**, No. 2 (1954).
[3] T. Nagata, Nature, **169**, 704 (1951).
[4] T. Nagata, Nature, **172**, 850 (1953).
[5] J. Hospers, Koninkl. Nederl. Akademie van Wetenschappen Amsterdam, Proc. Series B, **56**, No. 5 (1953).
[6] L. Néel, Ann. de Géophys., **7**, 90 (1951).
[7] J.R. Balsley, A.F. Buddington and J. J. Fahey, Trans. Amer. Geophys. Union, **33**, 320 (1952).
[8] T. Nagata, S. Uyeda and S. Akimoto, Journ. Geomag. Geoele., **4**, 22 (1952); T. Nagata, S. Uyeda, S. Akimoto and N. Kawai, *ibid.*, **4**, 102 (1952); T. Nagata, S. Akimoto and S. Uyeda, *ibid.*, **5**, 168 (1953).
[9] S. Akimoto, Japanese Journ. Geophys., **1**, No. 2, 1 (1955).
[10] T. Saito, Japan Geological Survey, private communication.
[11] T. Nagata and S. Uyeda, Nature, **175**, 35 (1954).

	KAWAZIRI-MISAKI BASALT		HARUNA DACITE
	R N R M	N N R M	R N R M
Age	Pleistocene	Pleistocene	Holocene
Declination	N 167° E	N 23° E	N 215° E
Inclination	−56°	+42°	−14°
$(J_n)_T - T$ (solid line) / $(J_{Tc})_T - T$ (dashed line)			
J_n / J_{Tc}	$4.8 \times 10^{-3} / 3.85 \times 10^{-3}$ emu/gr ~ 1.25	$11.8 \times 10^{-3} / 11.7 \times 10^{-3}$ ~ 1.01	$0.46 \times 10^{-3} / 1.4 \times 10^{-3}$ ~ 0.33
$J_s - T$ Heating (solid line) / Cooling (dashed line)			
Ferromagnetic Minerals	TiMt (spinel) a = 8.37 Å; Ht (rhombohedral)	TiMt (spinel) a = 8.400 Å; Il-Ht (rhombohedral)	TiMt (spinel) a = 8.403 Å; Il-Ht (rhombohedral) a_{rh} = 5.480 Å, α_{rh} = 55°08′
Curie point	540° C	480° C; 120°	460° C; 250°
Alternating Field Demagnetization $(J_n)_{\tilde H}$ (solid line) / $(J_{Tc})_{\tilde H}$ (dashed line)			
Characteristics of NRM	normal stable	normal stable	abnormal stable

	ICELAND BASALT		
	R N R M	N N R M	N N R M
Age	Early Quaternary	Early Quaternary	Early Quaternary
Declination	N 181° E	N 15° E	N 15° E
Inclination	− 75°	+ 78°	+ 78°
$(J_n)_T - T$ ——— $(J_{T_0})_T - T$ - - - - -			
J_n / J_{T_0}	$1.90\times10^{-3}/2.35\times10^{-3}$ emu/gr ~ 0.80	$1.17\times10^{-3}/3.45\times10^{-3}$ ~ 0.38	$1.56\times10^{-3}/4.60\times10^{-3}$ ~ 0.34
$J_s - T$ Heating ——— Cooling - - - - -			
Ferromagnetic Minerals	TiMt (spinel) a = 8.39 Å	TiMt (spinel) a = 8.49 Å (original) a = 8.43 Å (after heat treatment of 630°c, 1 hr, in the atmosphere)	TiMt (spinel) a = 8.397Å
Curie point	570°C	130°C 510°	500°C
Characteristics of NRM	very normal stable	normal rather stable	normal stable

	GEMBUDO BASALT		SUWA ANDESITE
	R N R M	N N R M	R N R M
Age	Pleistocene	Pleistocene	Pleistocene
Declination	N 196° E	N 77° W	N 128° E
Inclination	−40°	+40°	−75°
$(J_n)_T - T$ (solid) / $(J_{T_c})_T - T$ (dashed)			
J_n / J_{T_c}	$1.2\times10^{-3} / 2.5\times10^{-3}$ emu/gr ~ 0.48	$1.7\times10^{-3} / 8.6\times10^{-3}$ ~ 0.20	$1.3\times10^{-3} / 2.5\times10^{-3}$ ~ 0.52
$J_s - T$ Heating (solid) / Cooling (dashed)			
Ferromagnetic Minerals	TiMt (spinel) a = 8.476 Å (original) a = 8.401 Å (after heat treatment of 630°c, 1 hr, in the atmosphere)	TiMt (spinel) a = 8.490 Å (original)	TiMt (spinel) a = 8.382 Å, a = 8.429 Å
Curie point	120°C 500° (after heat treatment)	120°C 480° (after heat treatment)	490°C
Alternating Field Demagnetization $(J_n)_{\tilde{H}}$ (solid) $(J_{T_c})_{\tilde{H}}$ (dashed)			
Characteristics of NRM	normal rather stable	normal rather stable	very normal stable

Some Recent Studies of the Pre-History of the Earth's Magnetic Field

By J. A. CLEGG, Mary ALMOND and P. H. S. STUBBS
Physics Department, Imperial College, London

In 1952 a study of the remanent magnetism of certain sedimentary rocks of the Triassic system in Britain was begun in the Physics Department of the University of Manchester. This work was transferred in 1953 to the Imperial College of Science, London, where it has been continued and extended. Measurements have now been made not only on Triassic rocks taken from a wide area of England, but also on certain older sediments of the Carboniferous and Devonian systems.

The results provide strong evidence for the hypothesis that the land mass which now constitutes Britain has rotated at some period in geological history relative to the geographic poles. This rotation, which amounts to between 30° and 35°, may have occurred during the late Triassic era, or at some subsequent time.

The measurements have already been described and discussed in detail elsewhere, [1] and the present communication will be confined to a brief summary of the findings and conclusions.

1. The Triassic Rocks

The Triassic sediments sampled were fine red sandstones of the Keuper Marl series. Specimens were taken from a wide area of England (sites 1 to 10, Fig 1). The results are set out in Table I and the directions of remanent magnetism are shown on a polar projection in Fig. 2.

It is evident from the table that the specimens from the individual sites showed a marked uniformity of magnetic polarisation, and that they fell into two approximately numerically equal groups. Those from sites 1, 3, 5, 7 and 9 had mean horizontal directions of magnetisation lying between 26° and 45° East of present magnetic North, while those from sites 2, 4, 6 and 8 had horizontal directions of 28° to 66° West of South. Moreover, while the magnetic dips of the specimens were less consistent than the declinations, the rocks from the first group of sites all had downward dips markedly less than that of the present Earth's field in Britain (+65°), while, with the exception of the rocks from site 2, those of the second group all had shallow upward dips. In the case of site 2, the magnetic inclinations were widely scattered about zero, and had a mean value of +9°.

The rocks from site 10 showed random polarisations, and were found to be magnetically unstable. A possible reason for this instability is mentioned below.

Fig. 1

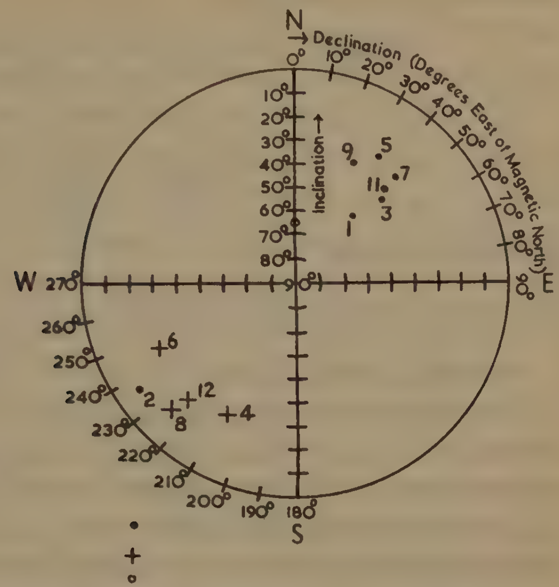


Fig. 2

· Downward dips + Upward dips
o Present Magnetic North

Table I. Results Obtained for Rocks of Keuper Marl Series.

Site no.	Locality	Nat. grid reference	Mean direction of downward tilt*	Mean angle of tilt	Total no. of specimens measured	Intensity of magnetization ×10⁻⁷ c.g.s.	Mean declination E. of M.N.†	Mean dip*	Radius of 50% circle of confidence‡
1	Frodsham, Cheshire	352.7E ; 378.2N	69½°	5½°	191	7.2	41°	+52° down	2.5°
2	River Dane, Cheshire	388.7E ; 368.9N	26°	8½°	33	9.2	236°	+9° down	1.5°
3	Holmes Chapel, Cheshire	377.8E ; 367.6N	186½°	7°	38	12.0	45°	+39° down	1.5°
4	River Bollin, Cheshire	381.3E ; 382.8N	260°	4°	37	35.2	208°	−28° up	1.5°
5	Wirral Peninsula	325.3E ; 387.3N	318½°	4½°	39	34.4	34°	+27° down	2.0°
6	Beaumont, Cumberland	335.1E ; 560.0N	172½°	36½°	37	12.8	246°	−27° up	1.5°
7	Carlisle, Cumberland	337.8E ; 556.6N	236°	5°	37	11.2	44°	+28° down	3.0°
8	River Trent, Notts.	464.8E ; 340.0N	84°	4°	119	6.3	225°	−16° up	1.5°
9	River Leven, N. Yorks.	446.1E ; 507.1N	107°	15°	9	140.5	26°	+22° down	1.5°

* Throughout this article the term "tilt" refers to the inclination of the bedding planes. The term "dip" is used to indicate the inclination of the remanent magnetization relative to the bedding planes.

† All azimuthal directions are measured East of Magnetic North in the plane of the strata.

‡ This has been computed by the method of Fisher (1953), Proc. Roy. Soc., A, **217**, 295.

2. Pre-Triassic Rocks

Two sets of samples of pre-Triassic age have been measured, one of Pennant Sandstone from the Upper Coal Measures of the Carboniferous period (site 11) and the second of Old Red Sandstone (Brownstone Series) (site 12). The results shown in Table II and Figure 2 are in general agreement with those for the Triassic Sandstones, the samples from the first site being polarised in a North-easterly direction with shallow downward dips, and those from the second in a South-westerly

direction with upward dips.

Table II. Results Obtained for Rocks of Old Red Sandstone and Upper Coal Measure Series.

Site no.	Locality	Nat. grid reference	Mean direction of downward tilt*	Mean angle of tilt	Total no. of specimens measured	Intensity of magnetization $\times 10^{-7}$ c.g.s.	Mean declination E. of M.N.†	Mean dip*	Radius of 50% circle of confidence‡
11	Frampton Cotterill, Gloucester	366.8E ; 183.2N	73°	19°	14	4.7	44°	+35° down	5.0°
12	Mitcheldean, Gloucester	367.2E ; 218.5N	277°	42°	39	6.7	244°	−22° up	5·5°

3. Stability of Magnetisation

Laboratory tests were carried out on numerous samples taken from the different sites, to find their stability when subjected to steady and alternating magnetic fields of different strengths. The results may be summarised as follows.

(a) It was found that while all the specimens (with the exception of those from site 10) were stable in the Earth's field at room temperature, the magnetisation could be readily changed by applying fields of the order of a few oersteds. Thus, when a specimen was placed in a slowly increasing field, the intensity $J(0)$ of magnetisation remained unaltered until the applied field strength reached a certain critical value H_c. This critical value differed from specimen to specimen, but always lay between 0.5 oersteds and 5.0 oersteds.

(b) When a specimen was placed in an applied field of strength H, greater than H_c, the magnetisation was found to change. The most notable feature of this change was that it depended not only on the value of H but also on the time of application. Thus, if readings were taken at intervals of a few minutes, the intensity $J(t)$ was found to increase rapidly at first, and then move slowly, finally reaching a steady value after a period of the order of a few hours. Conversely, when the applied field H was removed, the induced intensity $J(t)-J(0)$ decayed again in a similar time interval. For small values of $H-H_c$, $J(t)$ eventually reverted to the initial value $J(0)$, but for larger values of $H-H_c$, it approached a final value $J(\infty)\neq J(0)$. In the latter case, therefore, a permanent magnetisation $J(H)=J(\infty)-J(0)$ had been induced.

(c) The magnetic stability of the rocks decreased with increasing temperature. Thus at temperatures greater than 80 C the critical field H_c required to change the magnetisation of certain specimen became less than the field of the Earth.

(d) A number of specimens from the different sites were subjected to alternating magnetic fields of frequency 50 c/s. They showed a high degree of stability, the magnetic intensity remaining unchanged even when the applied field strength exceeded 300 oersteds.

(e) A. C. demagnetisation tests were also performed on specimens which had already acquired a permanent induced magnetisation $J(H)$ by the D. C. treatment described in (b) above. It was found that the induced intensity $J(H)=J(\infty)-J(0)$

could be reduced to zero by the application of A.C. fields of the order of 50 oersteds. A further increase in the A.C. demagnetising field beyond this point caused no further change and the specimen retained its original intensity $J(0)$ even when subjected to fields of the order of several hundred oersteds.

The interpretation placed on the results of these laboratory tests is as follows: The rocks contain two magnetic constituents, a hard component I and a soft component II. Component I is responsible for the remanent magnetisation. Component II is unmagnetised in the native rock, and is normally unaffected by the Earth's field, but is magnetised at room temperature in fields slightly stronger than that of the Earth, and at higher temperatures by the Earth's field alone. It is this second component which is responsible for the effects described in (a), (b) and (c) above.

The magnetic stability of component I is evident from the fact that laboratory specimens oriented in random directions in the Earth's field, and stored for several months, maintain their original directions and intensities of magnetisation. Evidence of stability over a more prolonged period is provided by the fact that the rocks from the various sites all have similar directions of magnetisation, and that these directions differ considerably from that of the present Earth's field.

A single exception to the foregoing statements is provided by the rocks from site 9. In this case the critical field H_c was evidently less than that of the Earth at room temperature.

4. Discussion of Results

Two facts clearly emerge from the foregoing results:

(a) The Triassic and earlier sediments sampled throughout England have a preferential direction of magnetisation which differs materially from that of the present Earth's field, the axis of magntisation lying in a North-Easterly—South-Westerly direction and having a shallow dip.

(b) In approximately half of the sites sampled the direction of magnetic polarisation was normal (i.e. North-East) while in the remainder the direction was reversed.

These two aspects can be considered separately.

(a) The N.E.-S.W. direction of polarisation

The mean azimuthal direction of magnetisation deviates by about 34° from the present geographic meridian. This difference is evidently significant, and its possible implications will be considered.

(i) The deviation might be due to a true difference in direction between the Earth's dipole field and the rotational axis at the time when the rocks acquired their magnetisation. This, however, is highly improbable, since recent theoretical and experimental evidence strongly supports the assumption that the main field [2] [3] [4] [5] [6] [7] corresponds to that of an axial dipole.

(ii) All the rocks examined were typical water-borne sediments, and their magnetic orientation might have been influenced by mechanical forces, such as those responsible for current bedding, at the time of deposition. But it seems highly improbable that specimens differing so greatly in geological age, and being distributed over such a wide geographical area, could all have been subjected to such uniform conditions during deposition.

(iii) Another way in which the preferential direction of magnetisation might have been produced is by the action of shearing strains on the rock after consolidation. There is, however, no geological evidence of any such distortion having occurred, at any rate in the case of the Triassic rocks.

(iv) Finally, the most likely possibility appears to be that the whole land mass of Britain has rotated through 34° relative to the Earth's geographical axis, at some period since the rocks acquired their remanent magnetisation. The mean magnetic dip of the rocks, which is appreciably less than that of the axial dipole field in Britain (+65°) also suggests a Northward movement of Britain. The extent of the latter type of movement is, however, more questionable, since the present dip may have been influenced by deformation or compaction after deposition.

A displacement of England such as that postulated here could be due to either of two causes. On the one hand it may represent a movement of the Earth's mantle as a whole relative to the poles (pole wandering), or on the other hand it could be due to a movement of the Continental land mass relative to the surface of the mantle (Continental drift). These two effects might be mutually operative and interdependent. It is hoped that by examining rocks of other ages, and from a wider geographical range, it will be possible to distinguish between them.

(b) Magnetic reversals

The fact that the rocks from six of the sites show normal (N. E.) polarisations, while those from the remaining five are reversed (S. W.), may be explained on the assumption of Earth's field reversal. Similar reversals have been observed in igneous rocks by Bruckshaw & Robertson, [8] and by Hospers [9] who put forward strong arguments in favour of a complete reversal of the dipole field. Alternatively, the observed reversals may be due to some physiochemical effect of the type suggested by Néel. [10] On the basis of the limited evidence at present available it seems impossible to decide this question with any degree of finality, and its elucidation must await further information concerning the constitution and properties of the magnetic constituents present in the rocks.

References

[1] Clegg, J. A., Almond, M. & Stubbs, P. H. S., Phil. Mag., **45**, 583 (1954).

[2] Bullard, E., 1949, Proc. Roy. Soc. A, **197**, 433.

[3] Runcorn, S. K., Trans. Amer. Geophys Union, 35, 49 (1954).

[4] Johnson, E. A., Murphy, T. & Torreson, O. W., Terr. Mag., **53** 349 (1948).

[5] Nagata, T., Rock Magnetism (Tokyo: Maruzen and Co.) (1953).
[6] Nagata, T., Nature, Lond., **169**, 704 (1951).
[7] Kawai, N., J. Geophys. Res., **56**, 73 (1951).
[8] Bruckshaw, J. Mc. G. & Robertson, E. I., Mon. Not. Roy. Astr. Soc., Geophys Suppl., **5**, 308, (1949).
[9] Hospers, J., Nature, Lond., **168**, 1111 (1951).
[10] Néel, L., Ann. de Géophys., 5, 99 (1949); Compt. Rend., **234**, 1991 (1952).

Sur les Aimantations Thermorémanente et Rémanente Isotherme du Sesquioxyde de Fer et de la Magnétite

Par Mlle Juliette ROQUET
Institut de Physique du Globe, Université de Paris

Résumé

L'étude des lois relatives à l'acquisition par les terres cuites et les roches des aimantations thermorémanente et rémanente isotherme et aux propriétés de ces aimantations a été reprise en détail sur des composés définis : sesquioxyde de fer rhomboédrique et magnétite en grains dispersés dans une substance inerte. Des généralisations, et des limitations d'ailleurs, ont été ainsi apportées aux lois connues et des faits nouveaux dégagés. L'effet des champs très forts a été particulièrement étudié, ainsi que les effets du traînage magnétique et de la dimension des grains des oxydes de fer.

Les aimantations rémanentes des terres cuites et des roches, leur application à la détermination du champ magnétique terrestre passé, ont fait l'objet de recherches étendues de E. Thellier [8 à 14]. Sous sa direction, j'ai repris l'étude des lois relatives à l'acquisition et aux propriétés des aimantations rémanentes, sur deux constituants principaux des terres cuites et des roches : le sesquioxyde de fer rhomboédrique $Fe_2O_3\,\alpha$ et la magnétite [7]. Ces oxydes, préparés par voie chimique, pour la plupart au laboratoire de Ch. Guillaud, à Bellevue, sont en grains fins (dimensions de l'ordre de 1/10 à $1/4\mu$). La magnétite, pure ou contenant quelques pour-cent d'impuretés : Fe_2O_3, Mn, Ca, Ti, fixées dans le réseau, a été dispersée, avec une concentration de 1% en poids, dans une substance inerte : le kaolin.

Un sesquioxyde de fer très pur (moins de 0,05% de FeO d' après Ch. Guillaud) possède la propriété, remarquable pour un tel oxyde, d'acquérir des aimantations quantitativement reproductibles d'un échantillon à l'autre, pourvu que les traitements magnétiques et thermiques aient été les mêmes.

Toutes les aimantations ont été mesurées à la température ordinair Lee. domaine des champs magnétisants a pu être étendu de 0,19 à 32,300 Oe. Il a été possible ainsi d'étudier des aimantations rémanentes analogues aux aimantations naturelles des terres cuites et des roches : aimantations acquises par refroidissement dans le champ magnétique terrestre ou, à la température ordinaire, par traînage dans ce champ, ou par action de la foudre.

La capacité d'aimantation du sesquioxyde de fer et de la magnétite évoluant par réchauffements, il convient tout d'abord de stabiliser magnétiquement ces corps,

ce qu'on obtient par recuit de longue durée à une température au moins égale à celle du point de Curie. Des refroidissements en champs de quelques milliers d'oersteds ont modifié profondément les propriétés magnétiques du sesquioxyde de fer très pur (accroissement de la susceptibilité, de la capacité d'acquisition d'aimantation thermorémanente et d'aimantation rémanente isotherme etc..), sans que des variations des paramètres cristallins soient décelables aux rayons X. Cette évolution des propriétés magnétiques reste acquise après désaimantation par réchauffement. Des refroidissements en champs de mêmes intensités n'ont eu pratiquement aucun effet sur les autres corps.

Nous allons voir que deux conclusions essentielles se dégagent de l'ensemble des résultats :

1°—les aimantations thermorémanente (A.T.R.) et rémanente isotherme (A.R.I.) du sesquioxyde de fer et de la magnétite présentent des propriétés communes mais dans des échelles de champs très différentes.

2°—les A.T.R. et A.R.I. de champs faibles ont des propriétés très différentes mais les A.T.R. et A.R.I. de champs forts ont des propriétés semblables.

Le sesquioxyde de fer est magnétiquement plus dur que la magnétite et, à champ égal, beaucoup moins aimantable.

L'A.T.R. est supérieure à l'aimantation induite, dans les champs faibles. Ainsi, le champ magnétisant étant de 0,42 Oe, le rapport Q de ces aimantations varie, suivant les échantillons :

de 13 à 595 pour le sesquioxyde de fer,

de 17 à 46 pour la magnétite.

Dans les champs faibles l'A.T.R. est également bien supérieure à l'A.R.I.. Dans les champs de l'ordre du champ terrestre l'A.T.R. varie linéairement en fonction du champ. Pour communiquer une A.R.I. appréciable à un échantillon, il suffit de quelques oersteds dans le cas de la magnétite ; le sesquioxyde de fer nécessite des champs beaucoup plus forts. La variation de l'A.R.I. σ en fonction du champ magnétisant H s'exprime par :

$\sigma = aH^2$ si l' A.R.I. provient d'une seule application de H.

$\sigma = aH + bH^2$ si l' A.R.I. provient de l'application de cycles $\pm$ H.

La saturation de la magnétite est obtenue avec des champs de quelques centaines d'oersteds pour l'A.T.R., de quelques milliers d'oersteds pour l'A.R.I.. L'A.T.R. et l'A.R.I. du sesquioxyde de fer paraissent tendre vers la même valeur quand le champ magnétisant augmente mais la saturation de ces aimantations n'a pu être atteinte malgré les champs intenses (de l'ordre respectivement de 8,000 Oe et 30,000 Oe) utilisés dans nos essais.

Stabilité des aimantations rémanentes.

Dans tous les essais de détermination du champ magnétique terrestre passé, qu'il s'agisse de sa direction ou de son intensité, on ne doit utiliser que des corps

(terres cuites, roches volcaniques, sédiments) dont l'aimantation naturelle est l'aimantation rémanente originelle acquise lors du refroidissement ou du dépôt [13].

L'étude, sur le sesquioxyde de fer et la magnétite, de l'action de plusieurs facteurs d'altération des aimantations rémanentes, a conduit aux résultats suivants :

a) *Action. à la température ordinaire, de champs opposés à l'aimantation.*

L'A.T.R. acquise en champs faibles est à peu près insensible à l'action de champs opposés bien supérieurs au champ magnétisant. Ainsi, l'application, en sens inverse de l'A.T.R. acquise dans un champ de l'ordre du champ terrestre, d'un champ H'_0 (dit champ de désaimantation) tel qu'il laisse une aimantation apparemment nulle, n'altère pas l'A.T.R. initiale ou ne la modifie que faiblement. Il y a, en fait, superposition, dans le corps, de l'A.T.R. et d'une A.R.I. de même valeur mais de sens inverse. Le champ H'_0 est plus important pour le sesquioxyde de fer que pour la magnétite. Par exemple, avec un champ magnétisant de 0,42 Oe :

$H'_0=905$ Oe pour le sesquioxyde de fer très pur,

$H'_0=66$ Oe pour la magnétite pure.

D'autre part, le champ H'_0 de désaimantation des A.R.I. faibles a une valeur égale (magnétite) ou très légèrement supérieure (sesquioxyde de fer) à la moitié de celle du champ magnétisant.

Pour un même corps, lorsque le champ magnétisant augmente, les champs H'_0 de désaimantation de l'A.T.R. et de l'A.R.I. tendent vers la même valeur, plus élevée pour le sesquioxyde de fer que pour la magnétite. H'_0 est de 200 à 300 Oe pour l'aimantation rémanente de saturation de la magnétite et de plusieurs milliers d'oersteds (jusqu'à 8,750 Oe dans nos essais) pour les aimantations rémanentes les plus fortes qu'on ait pu obtenir avec le sesquioxyde de fer.

b) *Action des réchauffements en champ nul.*

L'A.T.R. est d'autant plus sensible aux réchauffements que le champ magnétisant qui l'a provoquée est plus fort, l'inverse se produit pour l'A.R.I.. Les A.T.R. de champs faibles diminuent très peu par réchauffement jusqu'à des températures voisines de celle du point de Curie ; par contre, les A.R.I. faibles décroissent rapidement en fonction de la température de réchauffement. A mesure que le champ magnétisant et, par suite, l'A.T.R. et l'A.R.I., augmentent, on voit les courbes de désaimantation (figures 1 et 2) se déformer en sens opposés pour l'A.T.R. et l'A.R.I. et tendre vers une même courbe limite.

Lois des aimantations partielles.

E. Thellier [9 à 12] a établi, sur des terres cuites, trois lois relatives aux A.T.R. partielles de champs faibles. T. Nagata [1 à 5] a trouvé que les mêmes lois s'appliquent aux A.T.R. des roches volcaniques sauf dans le cas des A.T.R. en sens inverse du champ magnétisant.

Les essais sur le sesquioxyde de fer et la magnétite montrent que, pour ces corps, la première loi (loi d'additivité des A.T.R. partielles) paraît être valable quel

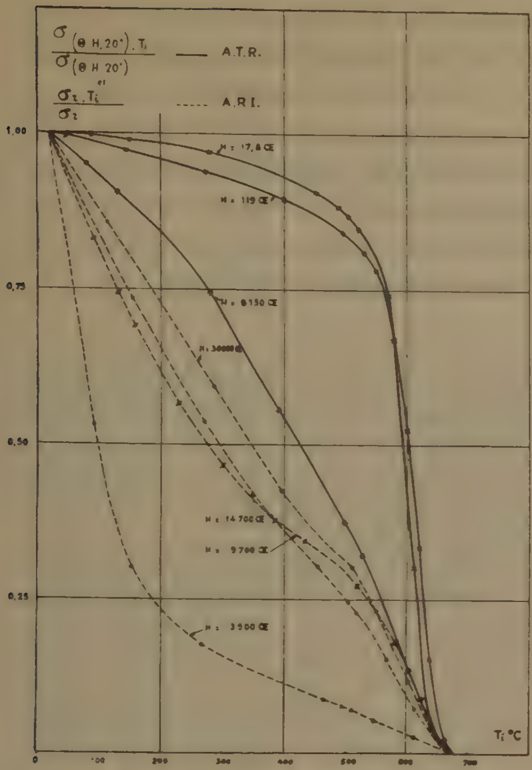


Fig. 1. Sesquioxyde de fer

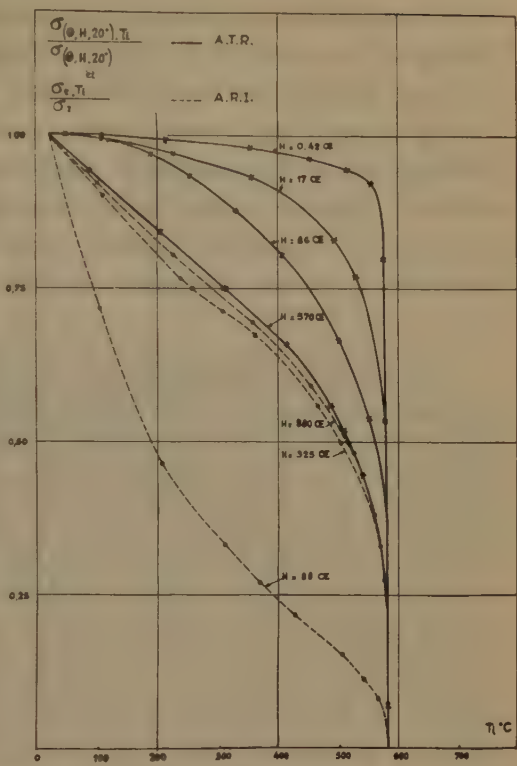


Fig. 2. Magnétite

$\sigma_{(\Theta,H,20)}$: A.T.R. acquise par refroidissement de $T \geqq \Theta$ (Θ point de Curie) à 20°, en champ H.

σ_r : A.R.I. acquise par application de cycles $\pm$ H.

$\sigma_{(\Theta,H,20),Ti}$ et $\sigma_{r,Ti}$: A.T.R. et A.R.I. restantes après réchauffement à la température Ti.

que soit le champ magnétisant ; en fait, il n'a pas été possible de faire des essais sur des A.T.R. supérieures à 65% de l'A.T.R. maximum.

Par contre, les deux autres lois, concernant la disparition des A.T.R. partielles par réchauffements, ne sont verifiées que pour des A.T.R. de champs faibles.

Les trois lois sont valables pour des champs magnétisants de l'ordre du champ magnétique terrestre.

c) *Action du temps.*

Dans le cas des aimantations rémanentes naturelles il peut y avoir superposition de traînages dans le temps : traînage spontané de l'aimantation initiale (A.T.R. ou A.R.I. de foudre), traînage de cette aimantation sous l'influence du champ magnétique terrestre, traînage de l'aimantation induite par le champ terrestre. Le problème du traînage dans le temps des aimantations rémanentes des terres cuites et des roches a d'abord été approfondi expérimentalement par E. Thellier [8, 9, 14], puis expliqué théoriquement par L. Néel [6].

Sur le sesquioxyde de fer et la magnétite, aucun traînage de l'A.T.R., sous l'influence du temps et du champ terrestre, n'a été mis en évidence, quel que soit le champ magnétisant. Le traînage des A.R.I. faibles, généralement de l'ordre de 1 à 3% en quelques jours, a été dans certains cas plus important ; par exemple, pour un échantillon de sesquioxyde de fer, l'A.R.I. acquise par application d'un champ de 880 Oe a diminué de 50% dans l'intervalle de temps (5 mn. 15 s.-4 jours), le temps étant compté à partir du moment de la suppression du champ. Le traînage de l'A.R.I. devient moins important quand le champ magnétisant augmente.

Des essais sur des échantillons d'argile de Noron, cuits en atmosphères diverses et ayant par suite pour principal constituant magnétique, en grains fins, soit le sesquioxyde de fer, soit la magnétite, ont confirmé les propriétés des aimantations rémanentes qui viennent d'être indiquées. Il en a été de même avec un basalte se comportant magnétiquement comme la magnétite en grains fins.

Les variations de l'A.R.I. étant, pour plusieurs de ces corps, suffisamment grandes pour être suivies avec précision dans le temps, on a constaté que, dans le cas du basalte et d'une argile riche en magnétite, les variations de l'A.R.I. étaient proportionnelles à celles du logarithme du temps écoulé depuis la suppression du champ. La variation relative de l'A.R.I. $\left(\frac{\Delta\sigma_r}{\sigma_r}\right)$ était alors, pour un même intervalle de temps et pour un même corps, de plus en plus petite à mesure que le champ magnétisant augmentait.

Les propriétés magnétiques des oxydes de fer dépendent beaucoup de la grosseur des grains (bibliographie dans [7]). L'étude d'une magnétite naturelle pulvérisée et dispersée (concentration 1% en poids) dans du kaolin, sous forme de gros grains (dimension moyenne $d=330\mu$) ou de petits grains ($d\simeq5\mu$), a conduit aux résultats suivànts :

la diminution de la grosseur des grains entraîne :

a) la diminution :

-de la susceptibilité χ de champs faibles,

χ passe de $470.\ 10^{-6}$ à $125.\ 10^{-6}$.

-de l'A.R.I. de champs faibles et moyens (jusqu'à 255 Oe) ;

par exemple, l'A.R.I. acquise en $H=2{,}9$ Oe a pour valeurs $0{,}37.10^{-4}$ et $0{,}03.\ 10^{-4}$ u.e.m..

b) l'augmentation :

-de l'A.T.R. de champs faibles,

à $H=0{,}42$ Oe correspondent des A.T.R. de $0{,}95.\ 10^{-4}$ et $5{,}95.\ 10^{-4}$ u.e.m..

-du rapport $Q=\dfrac{\text{A.T.R.}}{\text{aimantation induite}}$,

quand $H=0{,}42$ Oe, Q passe de 0,45 à 10.

-du champ de désaimantation de l'A.T.R. de champs faibles, pour $H=0{,}42$ Oe H'_0 est égal à 6 ou 58 Oe.

-de l'A.R.I. acquise en champs supérieurs à 255 Oe, les valeurs de l'A.R.I. de saturation sont 83. 10^{-4} et 215. 10^{-4} u.e.m..

-du champ de désaimantation de l'A.R.I. de saturation, H'_0 a pour valeurs 117 et 237 Oe.

D'autre part, l'A.T.R. acquise dans un champ de l'ordre du champ terrestre ne décroît spontanément dans le temps, ni pour les gros grains, ni pour les petits grains. L'A.R.I. traîne dans le temps pour les petits grains seulement.

Par suite, en supposant que les résultats qui précèdent puissent être étendus aux autres constituants magnétiques des terres cuites et des roches volcaniques, on voit que du point de vue de l'utilisation de leur aimantation naturelle pour la détermination du champ magnétique terrestre passé, les corps à petits grains seraient (pour une même composition chimique) plus intéressants que les corps à gros grains : A.T.R. plus fortes, plus stables, capacité d'acquisition d'A.R.I. plus faible dans des champs de l'ordre du champ terrestre. Dans les roches, les proportions de microcristaux et de phénocristaux sont variées, certaines roches se comportent comme les corps à gros grains, d'autres comme les corps à grains fins ou ont un comportement mixte. Sauf exceptions rares, les terres cuites ont le comportement magnétique des grains fins ; elles fournissent, par conséquent, des résultats beaucoup plus sûrs que la plupart des roches, d'autant plus que, contrairement à celles-ci, leurs capacités d'aimantation ne se modifient généralement pas par réchauffement.

Bibliographie

[1] Nagata T., Bull. Earth Res. Inst. **21**, 1 (1943).

[2] Nagata T., Nature **165**, 245 (1950).

[3] Nagata T., Akimoto S. et Uyeda S. Proc. Japan. Acad. **27**, 643 (1951).

[4] Nagata T., Uyeda S. et Akimoto S. Journ. Geom. Geoel. **4**, 22, (1952).

[5] Nagata T., Akimoto S. et Uyeda S. Proc. Japan Acad. **28**, 277 (1952).

[6] Néel L., Ann. de Géophysique **5**, 99 (1949).

[7] Roquet Mlle J., Thèse Fac. Sc. Paris (1953) ; Ann. de Géophysique **10**, 226 (1954). **10**, 282 (1954).

[8] Thellier E., C.R. Acad. Sc. **204**, 876 (1937).

[9] Thellier E., Thèse Fac. Sc. Paris (1938) ; Ann. I.P.G. Paris **16**, 157 (1938).

[10] Thellier E. et Thellier Mme O., C.R. Acad. Sc. **213**, 59 (1941).

[11] Thellier E., C.R. Acad. Sc. **213**, 1059 (1941).

[12] Thellier E., Notice sur les titres et travaux de E. Thellier, Paris (1941).

[13] Thellier E. et Thellier Mme O., Ann. de Géophysique **1**, 37 (1944).

[14] Thellier E., J. de Physique **12**, 205 (1951).

Reverse Remanent Magnetism of Dyke of Basaltic Andesite

By Y. KATO and A. TAKAGI
Geophysical Institute, Tôhoku University

and I. KATO
Institute of Mineralogy, Petrology and Economic Geology, Tôhoku University

The authors observed the remanent magnetism of a group of roughly parallel dykes of basaltic andesite, which were found traversing the narrow gorge of Ôkura river, near Sendai. Most of these dykes are formed with basaltic andesite, while the largest one consists of quartz-bearing andesite. Most of the dykes are the intrusion in green tuff as narrow dykes with 0.5~5.7 meters in thickness. The geological time when the green tuff deposited is estimated as Miocene and the time when the dykes intruded into the tuff is estimated as later Miocene or upper Pliocene.

In order to measure the magnetic orientation of these rocks, many specimens at every 50 cm interval from each of these dykes and the surrounding green tuff were collected. The magnetic declination and inclination of each specimen were determined by an astatic magnetometer by which the magnetic moment of 10^{-7}e.m.u. of specimen can be measured. The direction of the magnetization of all the dykes

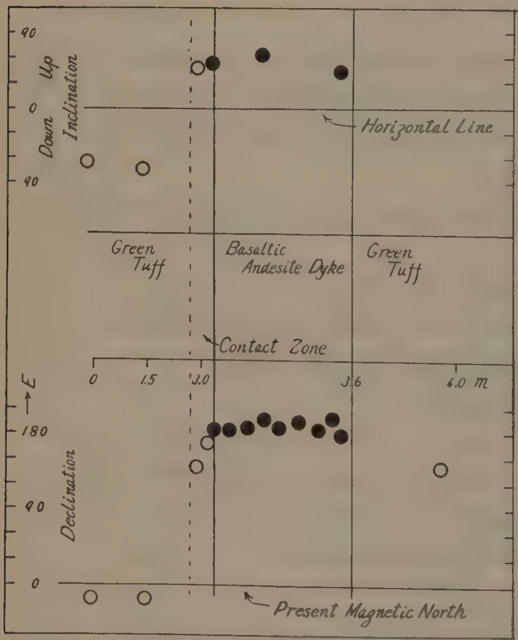


Fig. 1 Change of magnetic orientation of the intruded rocks near the intrusive body. (Dyke 3).

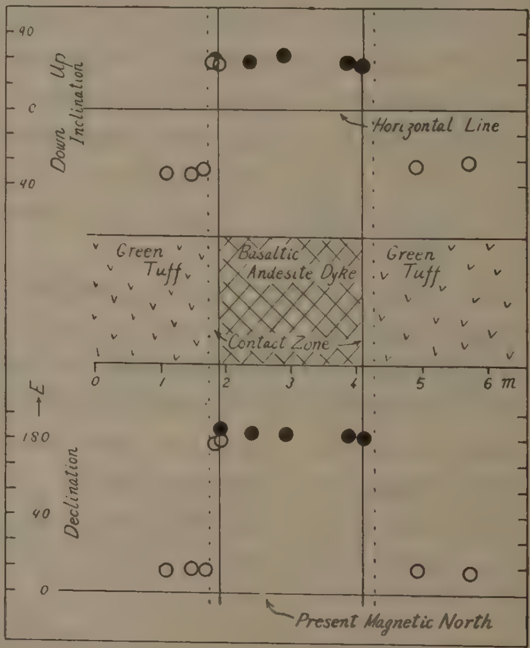


Fig. 2 Change of magnetic orientation of the intruded rocks near the intrusive body. (Dyke 5).

of basaltic andesite is nearly opposite to that of the present geomagnetic field; the mean direction is N183°E in declination and 58° up in inclination. The direction of the magnetization of the green tuff which just contacts with the dyke is the same as that of the dyke and is opposite to the present geomagnetic field, while that of green tuff, collected sufficiently far from the contact point nearly coincides with the direction of the present geomagnetic field, being N31°E in declination and 68° down in inclination. It is quite remarkable that the magnetic orientation of the green tuff rapidly changes towards that of the intrusive rocks as the position in the green tuff approaches the dyke. (Figs. 1 and 2)

On the other hand, the direction of the natural remanent magnetism of the quartz-bearing andesite is quite different from that of the above dykes and tuff; its declination is N89°E and inclination is 88° down. More precise examination of this anomalous characteristic of this quartz-bearing andesite with more specimens is under preparation.

The characteristics of thermo-remanent magnetism of the dyke rock of basaltic andesite and also of the green tuff were examined in laboratory. These rocks were heated up to about 900°C in an electric furnace and were cooled in the geomagnetic field. It is observed that the direction of the remanent magnetism of these samples thus acquired is just the same as that of the external magnetic field. It will be clear that these rocks possess the general characteristics of thermo-remanent magnetism.

Instability of Natural Remanent Magnetism of Rocks

By N. KAWAI
Geological Institute, Kyoto University

Geological evidence and experimental results have given sufficient confirmation for the fact that the natural remanent magnetic polarization of rock (abb: N.R.M.) is not always stable throughout the geological time, but by the renewed application of the geomagnetic force upon the specimen, the direction is changed even within a short period. The manner in which the change proceeds with time has closely been watched since these several years. The results illustrated in the Fig. 1 and

The time-change of N.R.M. of rocks.

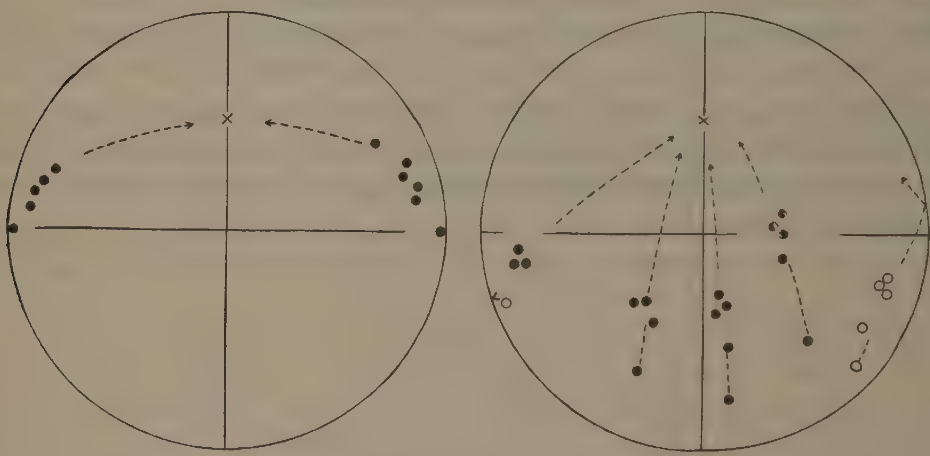


Fig. 1 Fig. 2

● positive pole on lower hemi-sphere
○ positive pole on upper hemi-sphere
× present geomagnetic field

Fig. 2 are those of the typical time-changes of N.R.M. of rocks, which soon after the sampling have been kept in laboratory with fixed orientation, the geomagnetic field being applied to the specimen in the direction nearly perpendicular to that of the original N.R.M. *in situ*. The changes, in most cases, have taken place in such a manner that the direction of remanent polarity tends to approach towards the magnetic field.

The stability and instability tests of rocks through the geological time up to the present were put into practice as follows. Many pieces of pebbles in conglomerate were sampled and the directions of their N.R.M. were measured. The polarity is estimated to be stable when these pebbles have retained the random directions of N.R.M. with which the pebbles had been put into the stratum. Whereas, it is concluded to be meta-stable when the direction of the N.R.M. of the pebbles have followed, or at

Table I—A Igneous Rock

Rock name	Locality	Direction of N.R.M.	Stability	Age
Andesite	Nara	Normal	meta-stable	
Dolerite dyke	Nara	NE72° dip 32°	stable	lower Plio.
Andesite	Kyoto	Normal	unstable	
Andesite	Kyoto	Reverse	meta-stable	
Basalt	Hyogo	Reverse	stable	
Basalt	Hyogo	Normal	meta-stable	
Andesite	Hyogo	Normal	meta-stable	
Andesite	Aomori	Reverse	stable	
Basalt	Toyama	Reverse		
Andesite	Osaka	Reverse	stable	
Andesite	Osaka	Reverse	meta-stable	
Andesite	Osaka	Reverse	meta-stable	
Basalt	Osaka	Reverse	meta-stable	Plio.
Dacite	Osaka	Reverse	meta-stable	Plio.
Sanukite	Osaka	Normal	stable	Plio.
Andesite	Osaka	Normal	meta-stable	Plio.
Andesite	Osaka	Normal	meta-stable	Plio.
Pitch stone	Osaka	Normal	meta-stable	Plio.
Dacite	Nara	Reverse	stable	Mio.
Andesite	Nara	Reverse	stable	Mio.

Table I—B Sedimentary Rock

Rock name	Locality	Direction of N.R.M.	Stability	Age
Ordinary Sediment	Boso	Normal	unstable	Pleisto.
Sand	Boso	Normal	unstable	Pleisto.
Clay	Boso	Normal	unstable	Pleisto.
Clay	Osaka	Normal	unstable	Lower
Azuki tuff	Osaka	Reverse	meta-stable	Pleisto.
Clay	Osaka	Normal	unstable	Pleisto.
Ordinal Sediment	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
,,	Boso	Normal	unstable	Plio.
Tuffacious Sediment	Boso	Reverse	meta-stable	Lower
Clay	Boso	Normal	unstable	Plio.
Volcanic Sediment	Boso	Reverse	meta-stable	Mio.
Shale	Boso	Normal	meta-stable	Mio.
Shale	Boso	Normal	unstable	Mio.
Sand	Boso	Normal	unstable	Mio.

least have had a tendency to follow, that of the geomagnetic field. However, when we could detect any appreciable change in the direction of N.R.M. by the repeated measurements in laboratory, it is concluded to be unstable. Thus the igneous and sedimentary rocks hitherto observed by us are classified into three kinds of groups, namely, stable class, meta-stable class and unstable class, the locality and the observed data of N.R.M., are tabulated in Table I with special reference to the above mentioned stability.

It should be noticed that the major part of the tertiary sediments reveals to be unstable except several volcanic sediments with reverse N.R.M. *e.g.* Azuki tuff in Ôsaka basin (Lower Pleistocene), tuffacious sediments in Bôsô basin (Lower Pliocene) *etc.*. On the other hand, greater part of eruptive rocks is classified either to stable or meta-stable class and the N.R.M. is considered to be better in stability as compared to that of the sediments. Several unstable cases aside, the data of eruptive rocks are in favour of interpretating the geomagnetic history.

The Interpretation of Reversed Magnetization in Igneous Rocks

By J. H. PARRY

Department of Geodesy and Geophysics, Cambridge University

It has been established (Gelletich, Bruckshaw, Hospers etc.) that reversed magnetization is not a rare phenomenon but occurs in continuous series of lava-flows and groups of dykes alternating with other series and groups showing normal polarization.

Two hypotheses have been put forward to account for this. An external agency namely the reversal of the geomagnetic field and an internal effect due to various suggested types of magnetic interaction amongst the ferromagnetic constituents of the rock. I propose to discuss critical evidence for this internal self-reversal of permanent magnetization.

Néel has suggested 4 mechanisms giving this effect.

Néel I, an anti-ferromagnetic effect within the crystal lattice of the magnetic minerals such as has been found in the spinel $Li_{0.5}Fe_{1.25}Cr_{1.25}O_4$ (Gorter, Schulkes)

Néel II, a similar effect in which an original inferior magnetization of the inverse B lattice becomes predominant by subsequent demagnetization or destruction of the originally predominant A lattice.

Néel III, a magnetic interaction between two distinct substances, perhaps intergrown, with different Curie points and temperature coefficients of spontaneous magnetization, in which the second cools through its Curie point in the resultant of the geomagnetic field and the demagnetizing field of the first thus acquiring a reversed magnetization superior to the normal one of the first.

Néel IV, a similar mechanism in which the originally inferior reversed magnetization of the mineral of low Curie point only becomes dominant after the destruction or demagnetization of the other.

Graham has suggested and to some extent demonstrated the occurrence of a fifth mechanism. This consists of a subsequent alteration of a part of an originally single magnetic constituent to some other magnetic form, particularly oxidation of magnetite to maghemite. It is suggested that despite the low temperature the new material will be magnetized in the demagnetizing field of the original substance. The unaltered material is supposed to be demagnetized later owing to its larger grain size, leaving a reversed permanent magnetization due to the alteration product.

The rock found by Nagata at Mt. Haruna which definitely shows this property of self-reversal when heated and cooled in the laboratory appears to belong to type

Néel III though certain experimental results obtained on it still require explanation.

The experimental methods so far used to investigate this problem are heating experiments, magnetic measurements at room temperature, mineralogical methods supported by physical studies such as X-ray photographs, and field studies:

Heating experiments are subject to the grave objection that alteration of the magnetic material is liable to occur but on the other hand such changes can be detected by the variation of properties other than those actually being measured in the experiments. It is perhaps most important to study only those rocks in which the thermo-remanent magnetization acquired in the present geomagnetic field does not differ in intensity by more than say 10% from the natural remanent magnetization in which case any very gross change can be eliminated. The decay of the natural remanent magnetization (N.R.M. after Nagata) with rise of temperature in zero field and the subsequent growth of thermo-remanent magnetization in the geomagnetic field as the temperature falls have been studied. Similarly the step-by-step destruction of N.R.M. and T.R.M. by heating to successively higher temperatures in zero field and cooling, again in zero field, to room temperature each time before measurment, has been carried out. Measurements of the curve of magnetization with temperature in fields of hundreds of gauss as carried out by Chevallier give an excellent value of the Curie point and are particularly sensitive to changes during heating. Given the variables of magnetic field, temperature and time many such experiments can be devised and in all cases changes such as oxidation which can be prevented must be by placing the specimen in a neutral atmosphere such as nitrogen or in a vacuum. The decay of N.R.M. and T.R.M. both continuously and partially seem significant as the rock was originally magnetized thermo-remanently and they give a measure of the temperature at which this took place and the relation to the artificial effect from which changes may be detected.

Magnetic measurements in the cold can consist of determination of the complete hysteresis cycle or removal of the remanent magnetization by steady or alternating fields etc.. The initial susceptibility depends on the concentration of the magnetic material and the shape of the grains while the saturation intensity depends on the concentration and the nature of the material. Hence if one of these three factors is known the others may be deduced. The coercive force of the hysteresis cycle is related only to the nature, size, and shape of the material. If two minerals are present with different saturating fields a change of slope of the magnetization curve should occur when the first reaches saturation; such an effect has not been found with certainty in many cases. The destruction of the N.R.M. by a steady opposed field, the so-called coercive force of remanence, in relation to a similar destruction by an alternating field has been shown by Graham to be useful in detecting the presence of two magnetic materials of different "hardness."

Since the magnetic minerals form only a very small part of most rocks and the relation between their composition and that of the other minerals and of the rock as a whole is almost unknown, the standard mineralogical and petrological

techniques of thin-section study and chemical analysis are not of great significance as yet. Polished section study is most useful in identifying the relationship between the ore-minerals, intergrowths and their development or disappearance on heating, oxidation products or the occurrence of irreversible changes such as that of maghemite to hematite. Complete and accurate separation of the ferromagnetic content from rocks so fine-grained as basalts is extremely difficult if not impossible; but even an imperfect separation can suffice to identify the minerals in question by X-ray methods, which is otherwise only possible by a Curie point determination where change may occur on heating.

Field studies show that reverse magnetization is not random, does not occur only in a particular petrological class of rocks and is related to similar reverse magnetization in sediments. Such considerations cannot be regarded as physical proof but they do point to a prima facie case for reversal of the earth's magnetic field requiring further investigation. Field work is needed to identify those rocks which are best to study where the magnetization, reversed or normal, is uniform within the rock and consistent from one flow to the next.

The minerals responsible for the magnetization of rocks and therefore those likely to be involved in the suggested modes of self-reversal are:

Magnetite and its solid solutions with Ulvöspinel, Fe_2TiO_4 giving the Titanomagnetites I; with Ilmenite $FeTiO_3$ giving the Titanomagnetites II (Chevallier); and probably with Maghemite (Hägg). The first two series have Curie points progressively lower than magnetite; data for the third are not available.

Maghemite $Fe_2O_3\,\gamma$ which is unstable and easily identified by its inversion on heating to haematite which is far less magnetic.

Haematite $Fe_2O_3\,\alpha$ which is only feebly ferromagnetic but may be of importance in igneous rocks, as it appears to be in sediments. Strongly ferromagnetic members of the solid solutions between haematite and ilmenite occur sparsely and may be of importance, that reported by Nagata in the Haruna pumice appears to be the first known occurrence in a lava,

The mineral sulphides of iron some of which are ferromagnetic are probably unimportant and are easily identified.

Impurities such as Mg, Na, Al etc. may modify the properties of most of the above but nearly always in the same sense and to a small extent in practice.

All these are anti-ferromagnetic.

With solid solutions, inversions, oxidations etc. many changes are possible in the normal history of a rock especially if there has been any degree of metamorphism, and during experiments, particularly heating.

Magnetite is liable to oxidation to maghemite or to haematite.

The titanomagnetites which with magnetite appear to be the most important in the basalts may exsolve into their end members; this has been shown to occur in slowly cooled rocks and may occur in time in basalts. There are indications of this effect in some Tertiary rocks, resolution occurring on heating. As in Graham's

theory of self-reversal the magnetization of a material thus exsolved below its Curie point is important.

Maghemite is not an original mineral in igneous rocks but after its production by oxidation of magnetite it may invert to haematite.

Haematite is the end product of these changes and is not likely to alter except under very strongly reducing conditions.

It is necessary to draw conclusions from the hypotheses of self-reversal which can be tested in the laboratory or in the field.

Néel I If no change has occurred in time or in heating, the reversal would be observed on cooling from above the Curie point; if a change involving loss of the property occurs on heating the T.R.M. will probably be different from the N.R.M. and the saturation magnetization will change; a change in time would cause demagnetization of both sub-lattices since they are magnetically interdependent.

Néel II Dr. R. Street has recently pointed out to us that this mechanism is probably impossible as the two sub-lattices of an antiferromagnetic can only exist owing to the strong negative exchange interaction between them and therefore the destruction or demagnetization of one would involve that of the other. If a change took place it is unlikely that the new substance would be magnetized in the direction of the inferior B sub-lattice.

Néel III is the most interesting mechanism as it does not require the presence of any hitherto unknown mineral and has been shown to occur by Nagata; if neither mineral has been altered or demagnetized in time or by heating, the effect will be observed in the laboratory as in the Haruna pumice. If the normally magnetized mineral which has the higher Curie point has been demagnetized the temperature at which the N.R.M. is destroyed on heating in zero field ("Curie point of N.R.M.") will be lower in reversed than in normal rocks, the re-magnetization of the first will be observed on cooling, the T.R.M. will be of higher Curie point and a reversal may be observed. If the first mineral has been altered the Curie point of N.R.M. will again be low and the alteration product should be identifiable magnetically or otherwise; in both the above cases a difference between A.C. and D.C. demagnetization should occur. If a change occurs on heating the point at which it sets in is identifiable by the temperature at which the curve of magnetization in high fields against temperature (Chevallier) ceases to be reversible; it may occur above or below the Curie point. In all cases to prove the occurrence of the Néel III or IV mechanisms it is necessary to show that the mineral of higher Curie point is or was magnetized in the opposite direction to the other mineral. If the direction of magnetization cannot be demonstrated the question must be left open. On the other hand, if it can be shown that two minerals of different Curie points are magnetized in the same direction, these mechanisms can definitely be excluded. This is apparent from the continuous destruction of N.R.M. in zero field with increasing temperature in the case of the Iceland basalts.

The problem of the magnetization to be expected when an originally homo-

geneous titanomagnetite exsolves at low temperature into two fractions of different Curie points or, as in Graham's hypothesis, when part of a finely intergrown magnetite is oxidised to maghemite, remains; Néel's treatment of the cooling of a mixture of two minerals is not strictly applicable since the first exsolved material will modify the field in which the exsolution will be completed whereas in the case of cooling all the material of lower Curie point is magnetized at one time and, the magnetization at that stage being small, the field is not modified. However if both materials are magnetized in the same direction the self-reversing mechanism is not applicable.

The self-reversal mechanisms so far proposed have been based largely on theoretical grounds. The arguments adduced against them and in support of reversals of the geomagnetic field have been mostly of an experimental and practical nature. The question will not be resolved until experiment and theory can meet and in particular until the properties of T.R.M. are better known and better explained.

References

Bruckshaw, J. McG. and Robertson E.I., Mon. Not. R. Astr. Soc., Geoph. Suppl., **5**, 308-320 (1949).

Chevallier, R. and Pierre, J., Ann. de Physique, **18**, 383 (1932).

Chevallier, R. and Girard, J., Bull. Soc. Chim. de France, **17**, 576-81 (1950).

Gelletich, H., Beitr. Angew. Geoph., **6**, 337-406 (1937).

Gorter, E.W., Philips Res. Rep., **9**, 295-365, 403-44 (1954).

Graham, J.W., Journ. Geoph. Res., **58**, 243-260 (1953).

Hägg, G., Zeits. Phys. Chem., **29B**, 95 (1935).

Hospers, J., Kon. Ned. Ak. Wet., Proc., **56B**, 467–491 (1953); *Ibid.*, **57B**, 112–121 (1954).

Nagata, T., Akimoto, S. and Uyeda, S., Proc. Jap. Acad., **27**, 643–645 (1951); *Ibid.*, **28**, 277–281 (1952).

Néel, L., Ann. de Géophys., **7**, 90–102 (1951).

Tracing the Earth's Magnetic Field in Geologic Time

By J. W. GRAHAM

Department of Terrestrial Magnetism, Carnegie Institution of Washington

Abstract

Magnetizations observed in selected flat-laying sedimentary rocks in the eastern United States suggest that during Paleozoic time the earth's magnetic field retained approximately its present day orientation. In contrast, the magnetizations of sediments in the folded Appalachian belt present a pattern of great complexity that in part, at least, can be explained on the basis of deformation. Pebbles embedded in conglomerates that field evidence indicates were once deeply buried and hence presumably raised in temperature, show uniformly the same direction of magnetization, one that departs significantly, though slightly, from the direction of the earth's field today. Conglomerates that were never deeply buried have polarizations that, though more scattered, are not completely at random. Pre-Cambrian acid and basic rocks—presumably akin to the source material of these sediments—show complex patterns of polarizations that are difficult to relate to uniform magnetizing field. A conservative appraisal of these observations is that the stability in time of magnetizations varied from sample to sample within unknown limits according to environment and constitution. The need still exists for developing combined laboratory and field procedures for identifying in rocks the magnetization which can be relied upon as valid indicators of past directions of the earth's magnetic field.

Nouveaux Résultats sur la Direction et l'Intensité du Champ Magnétique Terrestre dans le Passé Historique

Par E. THELLIER et Mme Odette THELLIER
Observatoire du Parc Saint-Maur

Résumé

Alors que la recherche du champ terrestre passé à partir des aimantations rémanentes des roches (volcaniques ou sédimentaires) continue à rencontrer des difficultés de principe considérables, cette recherche à partir de l'aimantation thermorémanente des terres cuites est remarquablement sûre et précise; sa limitation est seulement dans la précision de date et de provenance des matériaux archeologiques utilisés. Depuis l'Assemblée de Bruxelles, nous avons pu ajouter à nos résultats antérieurs des résultats nouveaux sur la direction du champ aux époques carolingienne et romaine, en Allemagne, Angleterre et Belgique, et sur son intensité à l'époque punique à Carthage et à l'époque romaine en Suisse.

The Remanent Magnetism of Varved Clays from Sweden.

By D.H. GRIFFITHS

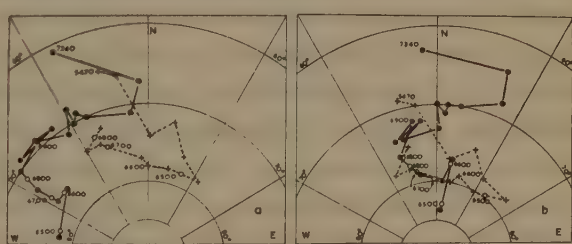
Department of Geology, University of Birmingham

If the remanent magnetism of sedimentary rocks is to yield information about the geomagnetic field in past times then the rocks must satisfy certain requirements. The period of their history in which the magnetism was acquired must be known, and its present direction must still be the same as the geomagnetic field at that time, or be related to it in an ascertainable manner. The investigations described below are an attempt to find out whether varved clays satisfy these requirements.

These clays possess a number of advantages over older and more consolidated rocks. They show an annual banding by means of which they have been accurately dated. Time intervals between layers can thus be determined, and correlation of deposits at different localities made. They have had a simple geological history, and also, being unconsolidate, they can be redispersed and resettled under laboratory conditions.

In the first instance orientated specimens from varve series covering approximately the periods A.D. 1000--A.D. 0 and A.D. 500--500 B.C. were collected from Prästmon and Undrom, two localities about five miles apart in Ångermanland, Sweden. These varves were originally precisely dated by Lidén [1] but only an approximate correlation was obtained between the series collected, though the error was small. The polarization directions were measured with an A.C. magnetometer, a modified version of the apparatus described by Johnson [2].

These directions, plotted on a stereographic projection, are shown in Fig. 1. (a), each point representing the average of five values. The mean deviations are 2°. It will be seen that there is considerable difference between the polarization directions for varves of the same age at the two localities. However, if the assumption is made that the layers were horizontal when deposited, and the magnetic vectors rotated to correct for the 3° dip of the beds at Undrom and the 12° dip at Prästmon, then quite close agreement is obtained



(a) (b)

Fig. 1. Directions of Remanent Magnetism of Swedish Varved Clays (a) Uncorrected and (b) Corrected for dip. Dates in years on Lidén's Time Scale where 7602 equals 1000 A. D. Prästmon. ●. Undrom +. Interpolated points ○.

between the two sets of values for points of corresponding age. The corrected values are shown in Fig. 1 (b). The mean difference between the directions for the four interpolated points for the years 6500—6800 (Lidén's time scale) is, before correction, 13°; after correction it is only 3°. For much of the two series both the range of the polarization directions after correction, and their rate of change are compatible with the view that they were mainly controlled by secular variation of the earth's field during deposition of the clay. It appears too that the polarizations have remained stable in direction. There are however irregularities and deviations, particularly in the youngest Prästmon varves. It is now believed that these are not due to magnetic instability but to current flow during sedimentation. This explanation is in accord with the geological evidence, which shows that the clays were laid down under relatively quiet conditions for most of the period, but that the velocity of bottom currents increased considerably towards the end of the time. It is also confirmed by experiments being done at Birmingham by Dr. R. F. King on the resettling of clay under controlled conditions. He has found that hydrodynamic forces acting during settling are important, currents of a few centimetres a second having quite large effects on the magnetization.

Since the correlation between the series from the two localities only appears after correction, it seems as if both sets of beds were deposited horizontally, and have been tilted since. The field evidence, on the contrary, indicates that the beds were part of a delta, and that the tilt is depositional. This contradiction has been resolved by the sedimentation experiments, which have shown that the effect on the magnetization direction of deposition on a slope is very roughly the same as if the clay has been deposited on a horizontal surface, this being tilted subsequently.

A year later, in cooperation with Professor Gustav Ising of Stockholm, the Geological Survey of Sweden, and the Oceanographic Institute of Gothenburg, varved clay cores were obtained from the present delta of the Ångerman River, using a non-magnetic Kullenberg core sampler carrying a device for recording the orientation of the samples. This device was designed by Professor Ising. This was the only method by which varves could be obtained recent enough for their polarization directions to be compared with observatory records of the geomagnetic field. Two continuous cores covering approximately the period 1300 A. D.—1900 A. D. were obtained, though owing to a failure of the orientation device the orientation of one core only (Core I) is known. The varves were dated by comparison with unpublished varve diagrams of other cores from the same locality prepared by Dr. E. Fromm of the Swedish Geological Survey. The geological dip of the beds was obtained by measurement on the core samples. The dips varied rapidly in some sections of the cores, and accurate measurement was not possible. This introduced an appreciable, but normally not serious, error into the corrected polarization directions, the dips being not more than a few degrees in most instances. Over 100 samples have been measured, and average values plotted as previously described. There is only a general agreement of trend between the total polarization vector

of the Core I samples, and the geomagnetic field direction for the corresponding date. This is true also for Core III, here it being necessary to choose an azimuth arbitrarily to give the best fit with the earth's field, and to assume that the core was sampled vertically. For both cores correction for geological dip slightly improves the agreement. If instead of plotting the total vector the declinations of the corrected polarizations are plotted, as shown in Fig. 2, then a fair measure of agreement between polarizations and known magnetic declinations is seen for the earlier part of the series, though the amplitude of the former is too large. It must be remembered when considering this agreement that owing to the steep magnetic inclination any scatter in the directions of the total vectors appears considerably magnified when plotted as declination. Inclinations are variable, but show a general decrease in the later varves to a value considerably less than that of the present field. This is again consistent with sedimentation experiments in which the horizontal polarization accurately reproduces that of the controlling field, but in which inclinations are always less. The form of the core sample results closely resembles that of the results for Prästmon, although in the cores the inclinations are less consistent. The geological environment during deposition is known to have been similar at the two localities, conditions being tranquil at first, but deposition of the later varves being disturbed by currents. Measurements have also been made on several short series of older glacial varves. These did not give conclusive data, but the results are consistent with those already described.

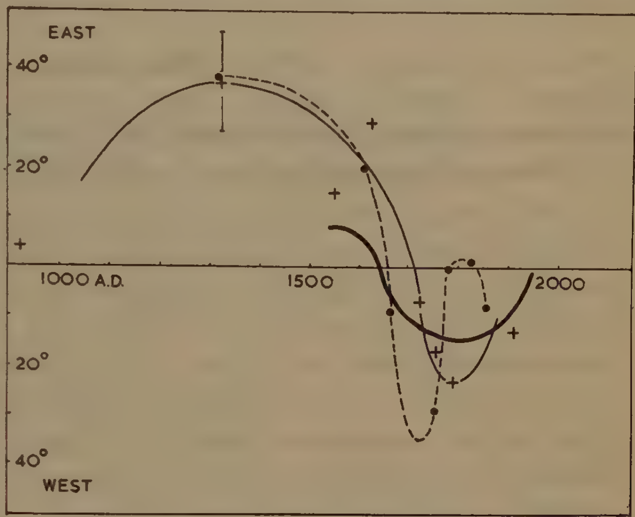


Fig. 2. Direction of Horizontal Component of Polarization of Varved Clays from the Ångerman River Cores.
● Core III. + Core I.
—— Declination from Observatory Data.
Mean deviations about 10°.

It seems reasonable to conclude tentatively that if a varved clay is deposited under quiet conditions the horizontal polarization will approximate closely to the geomagnetic field direction, but the inclination is likely to be less reliable. Unfortunately, although it is easy to correlate magnetic irregularities in the younger varves with disturbed conditions, this being evident in the coarseness and thickness of the layers, it is not usually possible to do so in the older and considerably finer grained material. So far it is not possible, therefore, to separate reliable from unreliable data on the field evidence alone, and it is thus not possible to use polarization measurements on such material to obtain precise data about secular

variation.

All the details of the sedimentation process are not yet fully understood, but it is hoped that further tank experiments will resolve the various difficulties still remaining. If strict quantitative relations can be determined it may well prove possible to use these to correct field measurements for the effects of currents etc. and so secure really accurate records of the past history of the field.

References

[1] Lidén, R., Geol. Fören. Förhandl., **60**, H 3, 397 (1938).
[2] Johnson, E. A., Rev. Sci. Instr., **9**, 263 (1938).

Discussion to Dr. D.H. Griffiths' Communication "The Remanent Magnetism of Varved Clays from Sweden"

By Gustaf ISING

I should like to add some remarks to Dr. Griffiths' interesting communication, as I have collaborated with him, partly through my former assistant, Mr. L. Granar, in the collecting of samples of recent fluvial deposits near the mouth of the Ångerman-river ("Ångermanälven") in northern Sweden.

Dr. Griffiths is to be credited for having promoted the magnetic study of these sediments in collaboration with Swedish geologists and physicists; I think the original instigation came from P. M. S. Blackett. It is, *a priori*, a very suggestive idea to test the reliability of "paleomagnetic" measurements on sediments of known age from, say, the last two or three hundred years, when direct determinations of the earthfield allow a comparison to be made.

For this purpose, the geologist C. Caldenius recommended the sediments around the mouth of the Ångerman river as offering an almost unique possibility of obtaining dateable varves up to our time. The present mouth of the Ångerman river is situated at Nyland, where the river flows out into the Nyland-firth: "The river there forms a delta which, on account of the quick landupheaval and the considerable depth of the primordial firth-groove, has no time to build up above the watersurface. The streampaths on the delta-plane go down to a depth of 5 m, the banks reach up to a little below the watersurface. The delta-plane is outwards limited by a steep discharge-bank, outside of which depths above 20 m very soon commence." (Quotation from a paper, in Swedish, by E. Fromm 1944).

Samples of the older fluvial sediments, mentioned by Dr. Griffiths, were dug out by him from the banks of the present river at Prästmon (about 8 km above Nyland) and at Undrom; while the youngest sediment samples, having an age from 0 to about 700 years, were taken up (1952) with a Kullenberg piston core sampler, made of austenitic stainless steel, from the bottom of the Nyland-firth at a water-depth of 65-95 m, about 3 km from the delta-bank. Of the four cores taken up, Nrs I and III were sent to Dr. Griffiths in Birmingham, while Nrs II and IV have been investigated in Stockholm by L. Granar, who also took a number of samples from core I (the orientation of which was most accurately known) for the purpose of comparison.—Glacial varved clay from the same region has an age of about 9000 years.

The fluvial sediments in their properties markedly diverge from glacial varved clay; the varve-boundaries are much less distinct and also their magnetic properties are somewhat different. For instance, when measuring the magnetic characteristics

of a number of samples, Granar found the dispersion (mean error) to be greater; this was especially marked in the declination of the remanent magnetization, which showed a dispersion 2-3 times greater than in glacial clay. It seems as if the river deposits during sedimentation had been more influenced by disturbances, probably of hydrodynamic origin, than is as a rule the glacial sedimentation—at least at some distance from the mouth of the ancient glacier stream ("distal" sediments).

Concerning such (hydrodynamic) disturbances, I wish to underline Dr. Griffiths' words in the last section of his communication: "All the details of the sedimentation process are not yet fully understood", and to emphasize the desirability of further experiments on artificial sedimentation, *e. g.* such as Dr. R. F. King has taken up in Birmingham. Of course, experiments ought to go hand in hand with some schematic theory of the sedimentation process in (slowly) streaming water, allowing quantitative calculations to be made. The simplest possible scheme considers the whole column of water, from the bottom to the surface, as sliding on its horizontal bed with a common velocity U, while the conveyed grains are sinking independently of U and of each other. This picture may, perhaps, allow a satisfactory calculation of the distribution of grain-sizes along the bottom of a deep and very slow current; but it is much too simplified for a general theoretic survey of the sedimentation process and the grain-orientation. Apart from the possibility of coagulation in concentrated suspensions, especially such of calciferous grains, also purely hydrodynamic disturbances ought to be faced. Mr. Granar, in his examination of natural sediments (to be published before long) has found distinct signs of stream-influence, especially on the magnetic anisotropy; and he has tried to improve the theoretic scheme by taking into account also the vertical velocity-gradient $\frac{dU}{dz}$ near the bottom of the stream.

昭和30年6月25日 印刷
昭和30年6月30日 發行
第6巻 第4號

編輯兼發行者 日本地球電氣磁氣學會
代表者 長谷川万吉

印刷者 京都市下京區上烏羽學校前
田中幾治郎

賣捌所 丸善株式會社京都支店
丸善株式會社 東京・大阪・名古屋・仙台・福岡

JOURNAL OF GEOMAGNETISM AND GEOELECTRICITY

Vol. VI No. 4

1954

Special Number for the Proceedings of the Palaeomagnetism Session, International Association of Terrestrial Magnetism and Electricity, Rome 1954

CONTENTS